

# THE ART OF ENGINEERING

presented to Larry Ellison

By David Kirkham

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Kirkham 427 KMS/SC—KMP0378

#### **INTRODUCTION**

One can not afford to neglect opportunity.

Sun Tzu, The Art of War

he person on the other end of the phone introduced himself as "Larry Ellison" and asked me, "What do you have in stock that I can buy right now?" I told him about a beautiful car we had just finished for Ford that we had displayed at SEMA 2005. He said, "Good. SOLD. We have a deal. How much?" After delivery, he expressed concern that someone could get hurt if they leaned against the hot, exposed side pipes—a burn known as a "snake bite." He asked if we could run the pipes out the back. I said we should consider making him a new car.

While we kept up a brisk communication about his next car with under-car exhaust, we began to consider other options we could feature within the framework of our cars. He mentioned he loved

the technology of modern automobiles and wondered if it would be possible to take the suspension off a new Z06 Corvette and put it under a Kirkham body. We bought a Z06 Corvette but soon discovered we couldn't shorten the leaf-spring suspension to the width of a Kirkham without too many dangerous compromises. We did, however, gather an incredible amount of good information on suspension geometry and kinematics by putting the Corvette on our lift and analyzing it.

Later, in the spring of 2006, Larry called. He was determined to commission a unique car but didn't quite know what he wanted. The conversation drifted:

Chopin Polonaises, Mountain Gorilla protection in Rwanda, sailing, the War on Terror, his love of classical guitar. He mentioned a Cobra was the most beautiful car in the world and casually asked me, "David, what do you want to build? What is your dream car?" I was floored. Ideas started racing in my head.

We had just been talking about our billet aluminum calipers we sell for the European FIA racing circuit. They look identical to the original cast aluminum calipers—except we make them from a solid

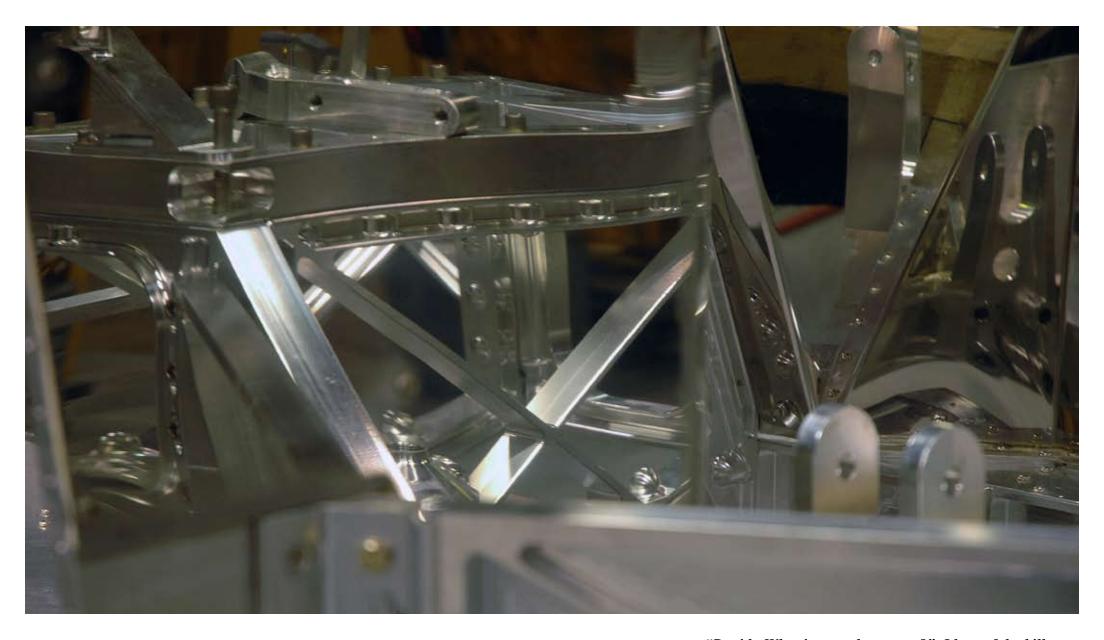
billet (block) of aluminum. They are extremely stiff and especially resistant to softening (losing stiffness) at the high temperatures encountered under heavy braking in race conditions. With our billet calipers, drivers are able to brake

a full 50 feet deeper into a corner than they can with the original cast calipers. I wondered out loud, "If we can make billet calipers, why not a billet chassis?"

Larry immediately jumped on board. He was very excited about the new project. This book documents the challenges, decisions, and solutions we encountered as we created this truly remarkable car. Resolve, imagination, and innovation are required to bring a car like this to life. This car started as a simple phone call and ended driving down the road. During the call, I told Larry I would make him the "best car I possibly could," a car with "no excuses."



Larry takes delivery of the Kirkham 427 KMS/SC—KMP0378—built for Ford to display at SEMA 2005.



"David...What is your dream car?" Ideas of the billet chassis began forming in my head.

We were faced with creating an entirely new type of chassis without the benefit of any "giant's shoulders to stand on." There were many fundamental engineering problems for making an aluminum billet chassis that had to be solved. The most difficult problem of all—the car had to be every bit as beautiful as any show car yet Larry was going to DRIVE the car not just look at it. His garages house a collection of cars that rival any in the world—Bentley GT, Ferrari Superamerica, McLaren F1, Bugatti Veyron to name a few.

To ratchet the pressure up a few notches, he told me he was going to "park it right next to his Bugatti

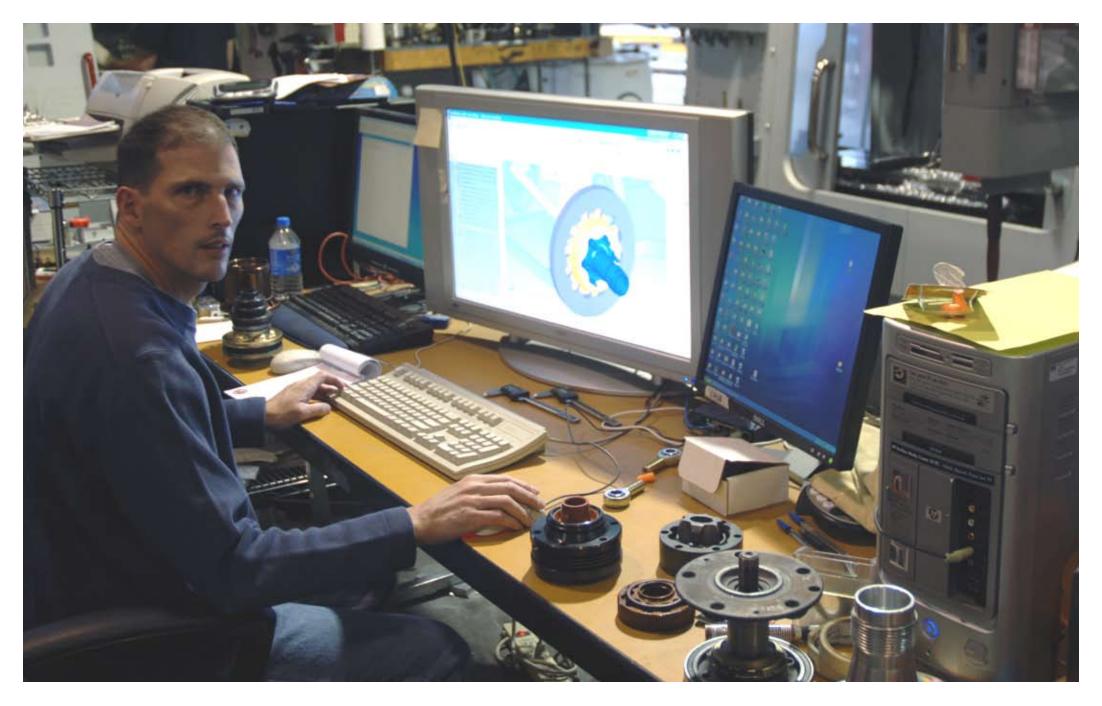
Veyron." We were up against the finest designers and automotive engineers in the world. We had to pull off something new, something innovative, something spectacular. Larry allowed us complete freedom of design to achieve that goal.

Throughout this book, there are pictures of two separate cars—a prototype and the actual car we delivered to Larry. We made a prototype car first to work out any unforeseen problems. You can distinguish the car we delivered to Larry in this book because we built his chassis with stainless steel bolts. The prototype car was assembled with black, steel bolts.

#### **BILLET CHASSIS DESIGN TEAM**

The greater danger for most of us lies not in setting our aim too high and falling short but in setting our aim too low and achieving our mark.

Michelangelo



CHRIS CINDRICH industrial designer

Chris Cindrich is a gifted industrial designer and Solidworks CAD jockey extraordinaire. Chris accompanied me on my first trip to Poland in 1995 to investigate the MiG fighter factory. He worked for over ten years as an industrial designer for Becton Dickinson. He is expert in ergonomics, aesthetics, and designing for manufacturability. In the above photo, Chris is working out the hub, axle, and constant velocity (CV) packaging. On the desk are an F1 CV, Porsche 930 axle assembly, and Viper CV. When we started, I asked him if he wanted to do a "little" CAD modeling.



DAVID CINDRICH machinist, programmer

David "Sandwich" Cindrich is one of the most talented, dedicated programmers and machinists on earth. He made every machined part on Larry's car. More than one part with errors of less than 0.005" ended up in the reject pile. There is over one ton of aluminum chips in the above box, and "Sandwich" probably made every one. We emptied it every week at the height of this project.



THOMAS KIRKHAM Jr.

mechanical engineer, VP Kirkham Motorsports

Thomas Kirkham Jr. is a mechanical engineer and VP of Kirkham Motorsports. He spent seven years as a flight-test engineer in the Air Force in charge of instrumentation on experimental aircraft. Thomas conceived of the entire suspension, based on his intimate knowledge of automotive theory and design. He is an extraordinary mechanical engineer who has an unbelievable natural grasp of automobile technology. In the above picture, he is using a laser to check for "bump-steer" in the front suspension.



A rare look inside the silent Polish aircraft factory when we arrived in March of 1995. Photography was strictly banned though I was able to obtain special permission to take a few photos. For scale, notice the man walking down the aisle. Aluminum forming dies for MiG fighters and other aircraft fill the dusty shelves. Other men stood behind silent machines. The lights were off.



DAVID KIRKHAM

entrepreneur, President Kirkham Motorsports

I started Kirkham Motorsports in the fall of 1994 during my senior year at Brigham Young University where I studied Spanish Interpretation, Manufacturing Engineering, and Pre-Med. One day my brother and I found ourselves looking at a relic of the Cold War—an old jet fighter airplane made at a factory in Poland that was desperate for work. My brother turned to me and said, "These guys could make an aluminum-bodied Cobra!" Captivated by this once-in-a-lifetime opportunity, I packed my bags and left BYU and my dreams of medical school behind. I landed in Poland with a toy model of a 1965 Ford Cobra, a Polish-English dictionary, and a new dream. In the above picture, I am sitting by our electric super car 1/5 scale model.

# SUSPENSION DESIGN

Every difficulty slurred over will be a ghost to disturb your repose later on.

Frederic Chopin



Over 1500 hours were spent designing the chassis.

Larry didn't want any modifications to the shape of our car—which presented some challenging constraints on the design of the vehicle. Handling was our top priority, so we started with suspension design. We digitized one of our cars and placed the body and wheel data into a computer to establish a baseline to work from. Then, we put in the CAD data for the engine, transmission, and differential. Next, we designed the best suspension kinematics we could possibly fit in the area we had to work with between the wheels and around the engine and other parts. When we finally had the suspension exactly how we wanted it, we designed the chassis to the suspension pick-up points.

Obviously, suspension design is critical to the handling of the car. My brother Thomas has spent his life studying race cars. His expertise was invaluable to

create the proper kinematics of the suspension. The suspension was designed as a short-arm, long arm (SLA) suspension patterned after almost all modern, purpose-built race cars. We worked very hard to come up with the best "street" suspension that could possibly be made to fit in the package we had to deal with. Many "Hot Rodders" mistakenly think they want a "race car" suspension when, in fact, it would be totally unacceptable for street use. A race car suspension would be much too stiff and harsh for street use. Also, an F1 suspension typically has very little travel because the less a suspension travels, the easier it is for the engineers to control the camber and toe change of the wheel. However, bouncing off curbs and potholes on the street with F1 suspension rates will quickly make the driver's eyes blur.

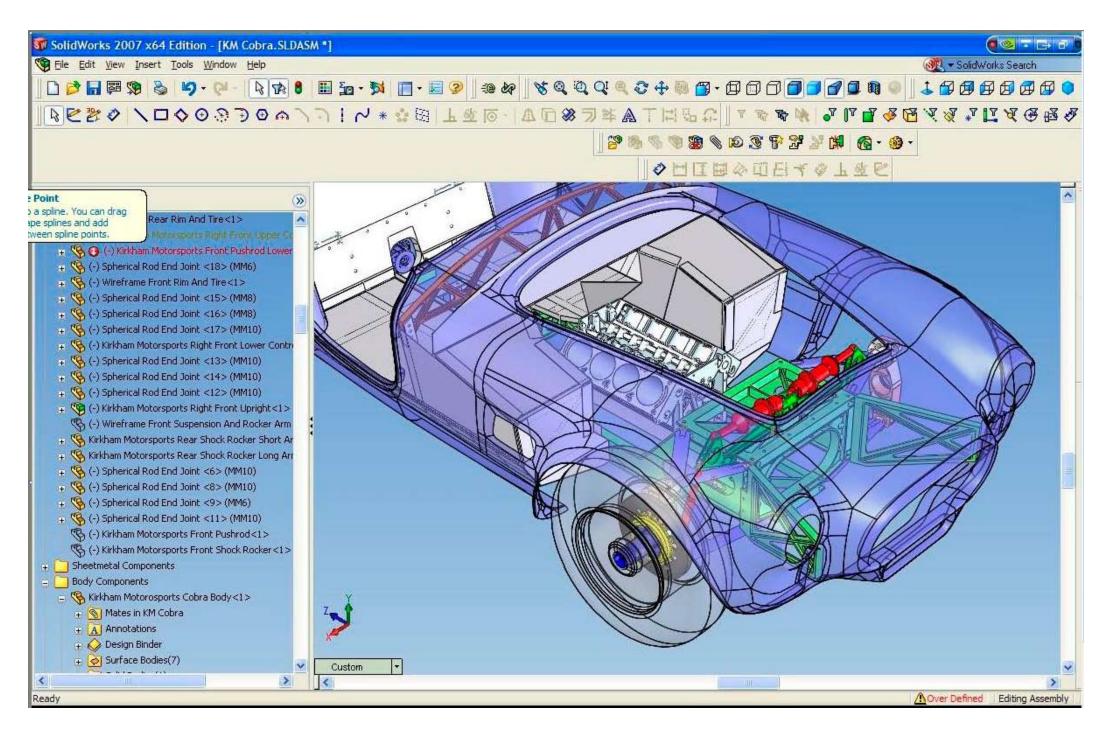


Digitizing the body shape.

We needed the entire body—with all the substructure tubes, engine, transmission, seats, interior panels, wheels, and differential—in a CAD model to define the boundaries of the car, as we were not going to change the shape of the car. The CAD model provided an accurate datum so everything could be packaged correctly. In the above picture, everywhere the tape lines cross on the body, a point is taken by the digitizing arm and recorded in an X, Y, and Z dimension. The points are then "stitched" together into a surface by the computer.

We used the CAD data when designing the suspension and chassis to fit all the parts correctly in

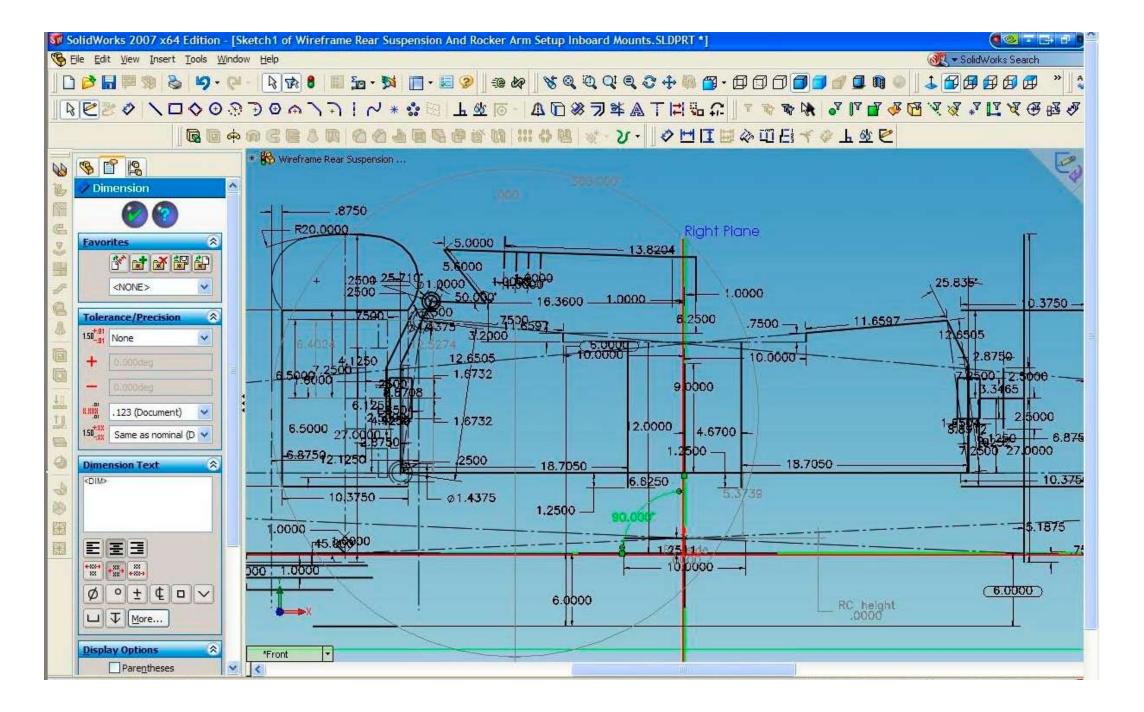
relation to each other. With Solidworks (a CAD modeling program), we were able to virtually move the suspension model up and down and evaluate the kinematics of the suspension throughout its travel. "Bump steer" (the change in toe as the suspension moves up and down) is a vexing problem in any suspension design. If the toe changes too much under travel (or in an undesirable direction), the driver will describe the car as nervous, vague, unpredictable, or even scary. The original Cobra has "puckering" bump steer characteristics. As all drivers of an original car can tell you, sometimes they don't know which end of the car is doing the steering.

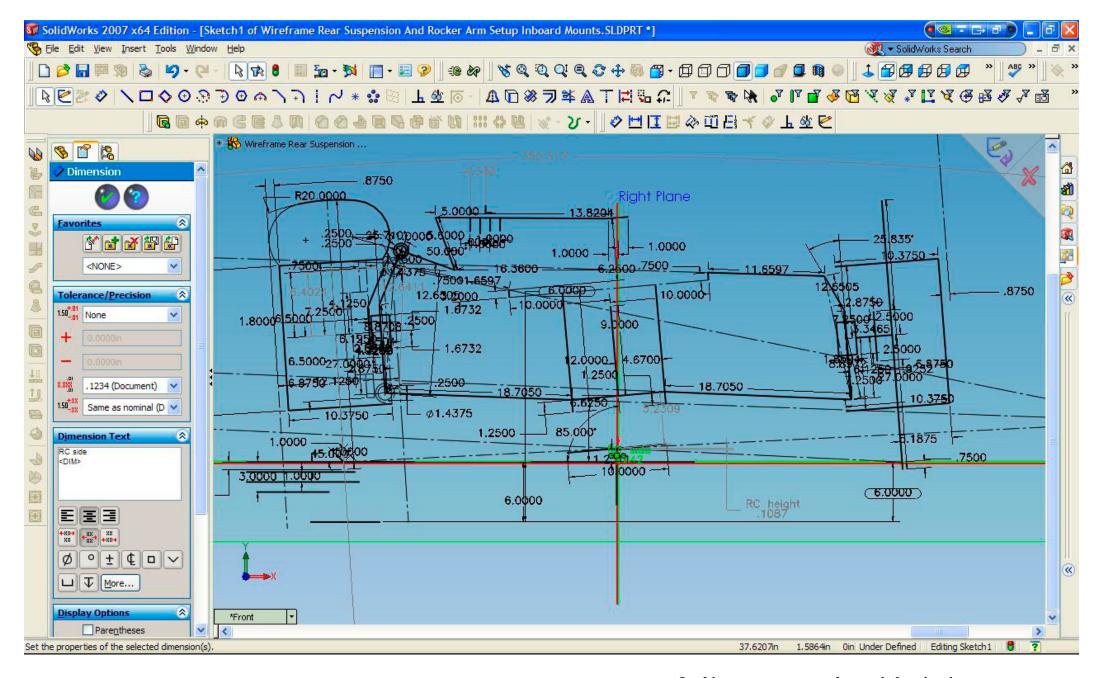


The first thing we did on the computer was to place the body over the wheels to see how much space we had to work with to design the suspension.

The kinematics of a suspension determine how a car handles under the varying situations encountered while driving. The suspension must perform well in ride (hitting a bump or a pot hole), roll (leaning into a curve), braking, and acceleration (pitch). Transitions from one state to another must be taken into consideration as well. When weight transfers forward in braking, the chassis must not become unstable for the upcoming turn. As the wheel moves up, the wheel needs to move in at the top (camber gain) so as much of the contact

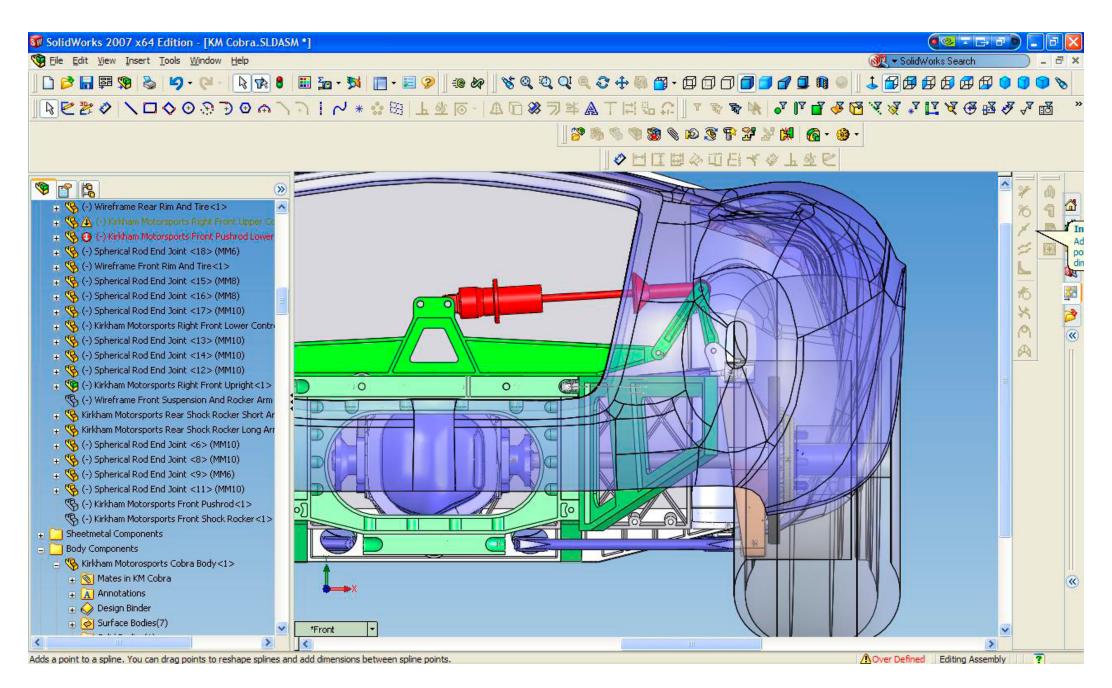
patch of the tire remains on the road as possible. Even slight adjustments in the suspension require considerable hours to set up and evaluate. This was the most time-consuming part of design phase for the project. It would be impossible to design an adequate suspension without a CAD system because the wheel has to be controlled in 6 axes of movement at all times. The number crunching is intense. The below screen capture of Solidworks shows the left wheel moving up and down while the right wheel stays stationary.





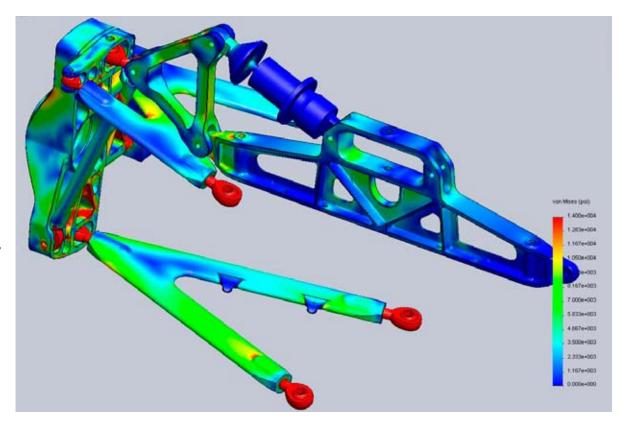
In this screen capture, the car is leaning into a corner as if the car were turning to the right and the weight were shifting to the left. The "center" about which the car "rolls" is called its "roll center." The roll center of the front and the rear need to be close to each other so the car does not become unstable in a corner.

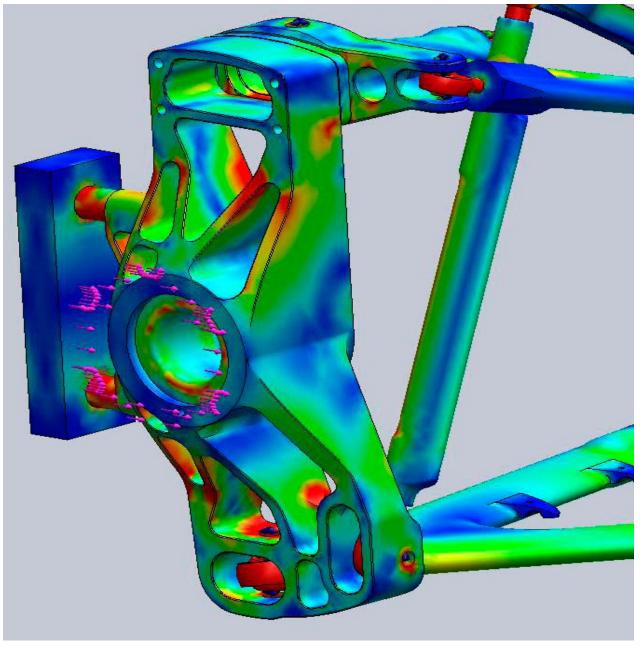
Opposite: Solidworks allowed us to design the suspension to the best possible kinematic compromise for the given package.



This is the first version of the suspension we designed; we later updated it with lighter parts. The rear lower control arm is placed horizontal at ride height so the tire scrub is minimized for the first up and down movements of the chassis. The body is translucent to check for any interferences.

The different colors in FEA (Finite Element Analysis) represent different stress levels in the suspension. Blue represents the least amount of stress and red the most. The rod ends are red because we told the computer they were made out of the same 6061 aluminum alloy as everything else (to simplify the number crunching). The rod ends are actually made of high strength, 4340 chromoly steel, nickel plated to prevent corrosion. The entire suspension was modeled in FEA—maximum braking, maximum acceleration, maximum compression, and maximum rebound.



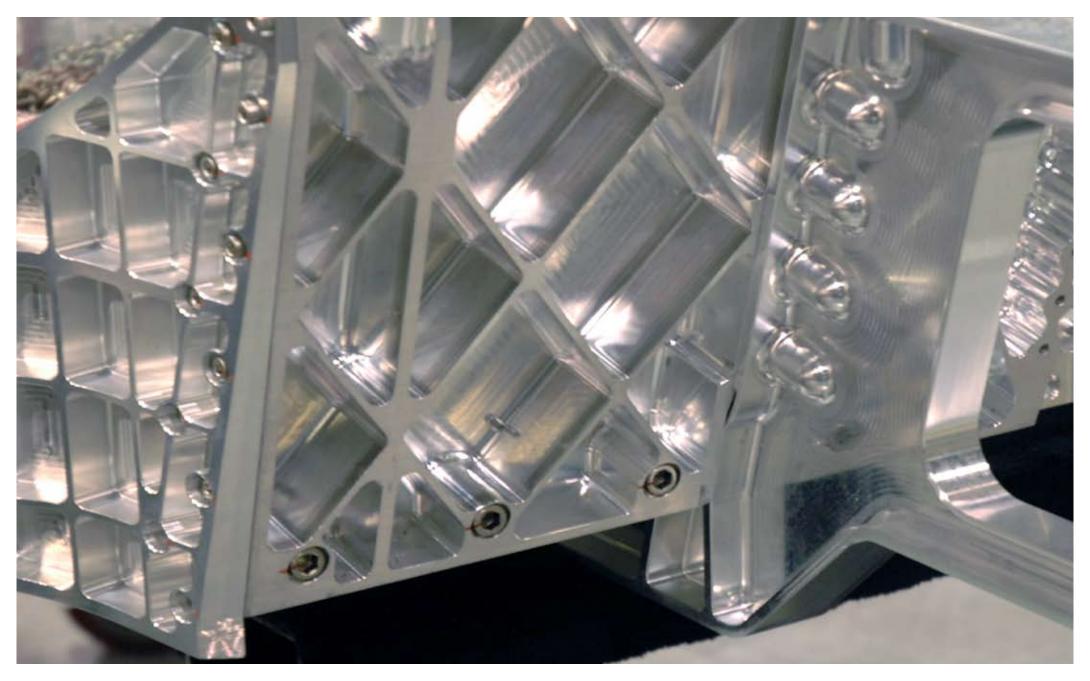


In these pictures, you can see why we call FEA "Looking for rainbows." Red areas in the upright signal areas that need attention. Most interestingly, sometimes you can actually remove material in the red areas and make the part stronger and lighter at the same time.

#### **BILLET CHASSIS**

 $\it No\ problem\ can\ stand\ the\ assault\ of\ sustained\ thinking.$ 

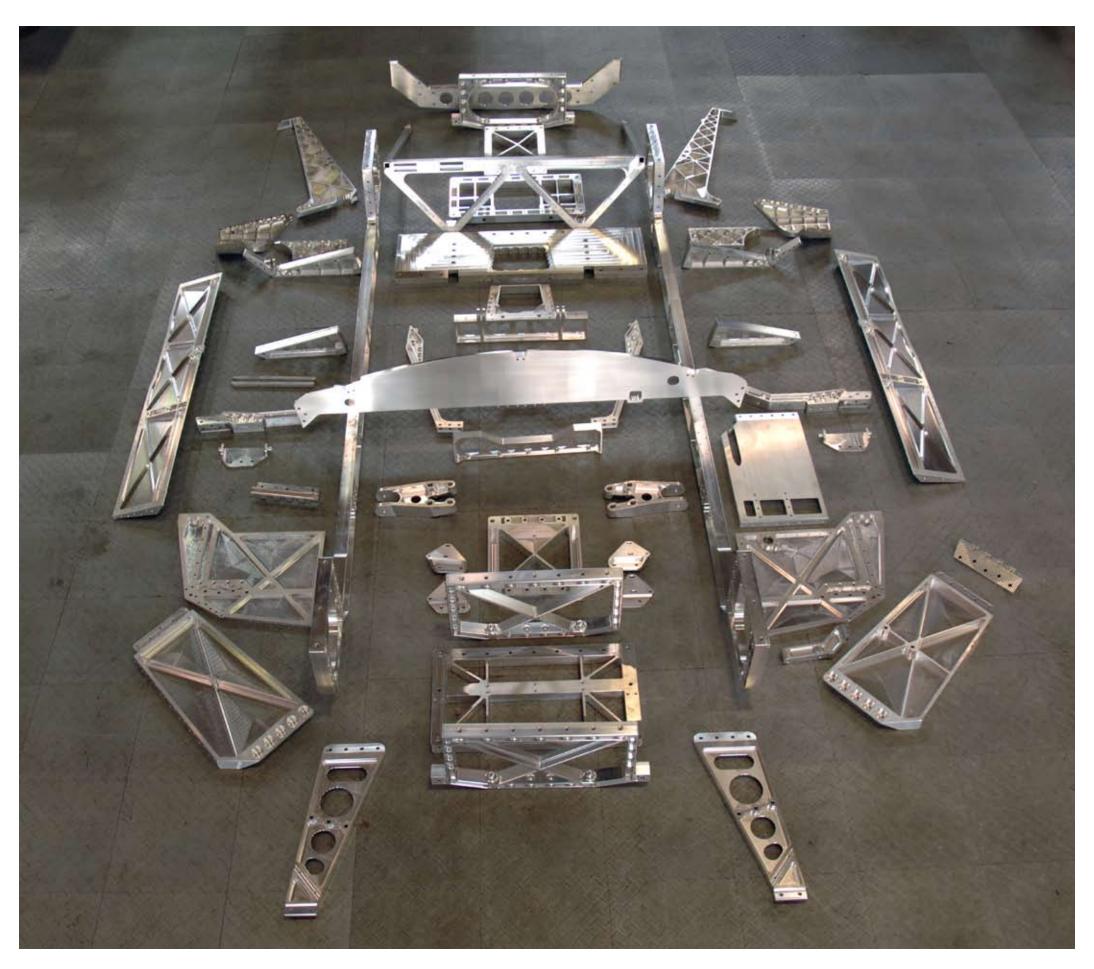
Voltaire



It's astonishing. What a magnificent metal sculpture.
—Larry Ellison

We could have used any number of materials to make the chassis—carbon fiber, steel, even stainless steel. Why did we choose billet aluminum? Steel construction has been around for over 100 years, and we wanted to do something no one had ever done before. Aluminum is light, strong, and machinable into exceptional shapes—limited only by the machinist's creative mind and will to succeed. Engineers dream of making products that will solve whatever problem confronts them. A solid block of aluminum demands to

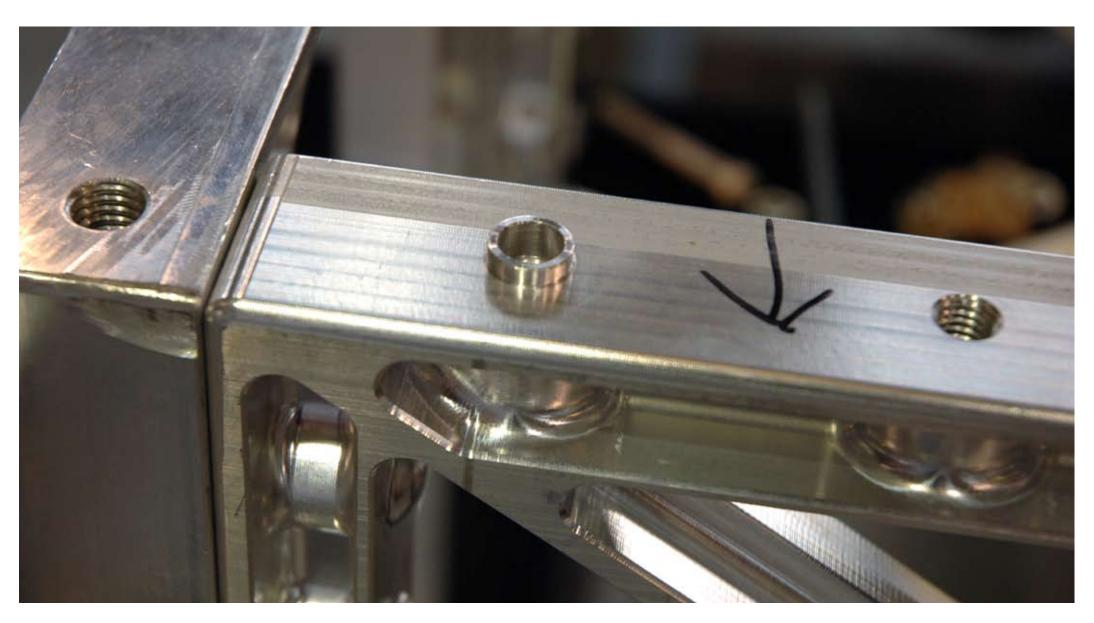
be carved into something useful, something beautiful. Though a simple block of aluminum will suffice to make a seemingly insignificant bracket, what would happen if that bracket were given to an engineer to make it lighter, stronger? What would happen if that engineer then exercised strict weight discipline to make it even lighter still—say, to the extreme? What would happen if we then gave the engineered bracket to an artist who could transform harsh engineering edges into a graceful genesis of beauty?



All of the parts that make up the billet chassis. There are thousands of holes and myriad angles that all have to line up—and work.

The world has never seen a billet chassis, although when I proposed it to Larry, I couldn't see a reason why one could not be made. But, when I called our friends and customers in the racing world and asked them about an aluminum chassis, they all told me I was crazy. They told me about the 1971–1972 Porsche 917 chassis that were made out of aluminum and prone to cracking failures. To predict the failures, Porsche welded Schrader valves into their chassis tubes and mounted a gauge onto another bung in the chassis. Before a race the team pressurized

the chassis with air; every time the car came into a pit stop, they checked the pressure gauge. If the chassis lost pressure, they knew they had a fatigue crack somewhere in the chassis. Porsche engineers are very bright; if they thought aluminum could save them weight, then I reasoned I should be able to use it as well. I just had to figure out how. Welding was not an option, as welding takes the heat treat out of aluminum, cutting its strength in half (as evidenced by the Porsche 917s). There had to be another way.



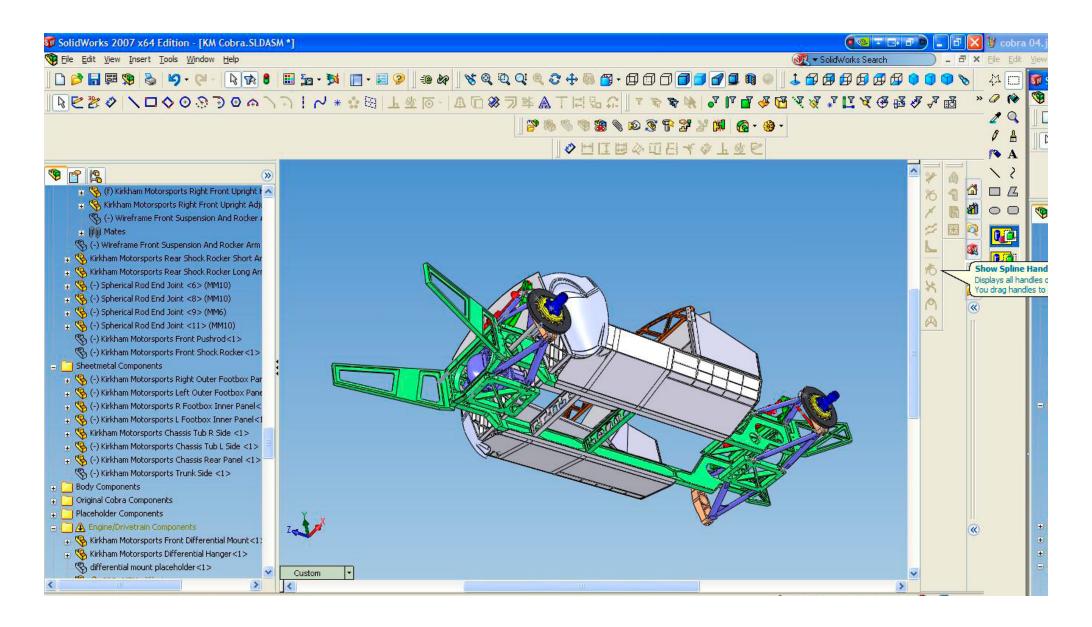
Chassis components are doweled together—like an engine's connecting rod. The bolt then passes through the dowel.

I began to notice highly stressed parts were bolted together—heads were bolted onto engine blocks and brake caliper halves were bolted together. Maybe I could bolt a chassis together as well. The last key to solving the puzzle came when I looked at a connecting rod and noticed the two halves were bolted together. The rod and cap halves were aligned by a hollow dowel. We could bolt the chassis together the same way—problem solved!

Countless hours were spent thinking, engineering, designing, programming, revising, and creating this car. One of the problems with the original Cobra is the

suspension pick-up points are not in the optimal place. This is not the fault of the original designers because back in the 60's, they didn't have the benefit of CAD and CNC machinery to make their parts. Utilizing the latest technology, we knew we could make a better car. When a tubular steel chassis is welded together, it always warps from the welding process. When the steel tubes warp, suspension pick-up points move all over the place, messing up the kinematics of the suspension. Exact CNC milling, then doweling and bolting the chassis together, allowed us to hold the suspension points exactly where we designed them to be.





To get a base-line for our design, we digitized an original chassis and ran it through FEA (Finite Element Analysis). In FEA we can take a part and stress it so we can see what is happening to the part as it goes down the road. If an area of a part flexes too much, we add material to stiffen the part. If an area of a part is too massive and doesn't flex at all, we remove material to even out stresses and save weight.

As we flex a part in the computer, the program colors the part with different colors. The different colors represent varying levels of stress that are induced into the part by loading it. By analyzing an original chassis, we discovered the original 427 Cobra chassis had a stiffness of 1450 foot pounds/degree of deflection. Analysis of the billet aluminum chassis

showed a stiffness of close to 4500 foot pounds/degree of deflection, or a 300% improvement over an original chassis (actual stiffness is a little lower because we did not perfectly model the bolted-together joints).

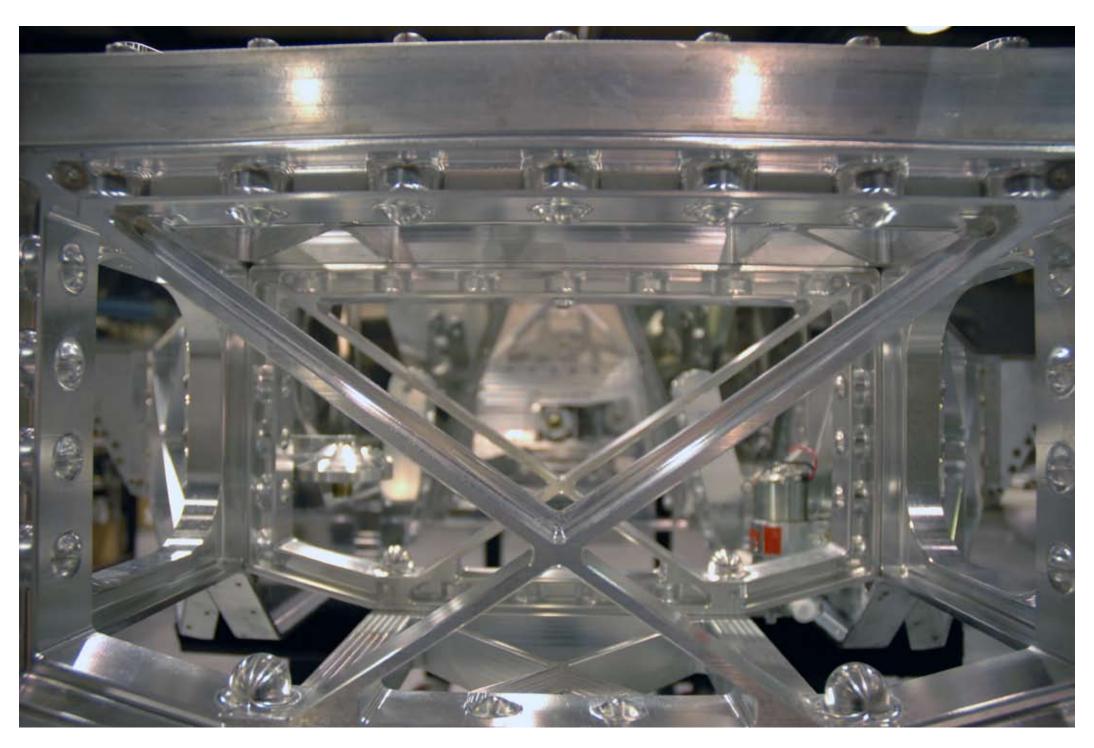
In the main frame tubes of the cars we currently make, we use a 0.035 inch thicker tube than what is used in an original car. The thicker tube increases our chassis stiffness (over an original chassis) by 14% to 1650 foot pounds/degree of deflection.

Even a seemingly small 14% increase in stiffness in a chassis is quite noticeable to a driver. For comparison, a "super-car" (like a McLaren F1) typically has a stiffness of 10,000 foot pounds/degree of deflection—though a super car has a roof, which is an enormous help in torsional rigidity.

How did we get the stiffness so high, especially considering aluminum is only one third as stiff as steel? The stiffness of an object depends on the material used to make it (think glass is stiffer than paper) and the geometry of the object itself (think of a flat sheet of paper vs. a box made out of that same paper). We were able to increase the stiffness of the billet chassis by using tall door sills and spreading them far apart. We also made an innovative billet aluminum bulkhead in the rear to carry the suspension loads forward. The structure of the chassis is very similar to how an airplane is built with a stressed outer skin on longerons.

We bolted the sheet metal down to long frame rails to transfer as much of the load as possible to the outer surfaces of the sheet metal. We separated the floor pan from the belly pan by 4 inches (the height of the frame rails). We moved the sheet metal as far apart as possible because the further you can move mass from the neutral axis, the stiffer a part will be (think about an "I" beam). Finally, we stressed the tunnel to help transfer the loads front to rear. In fact, we made every part possible perform multiple duty—achieve its original function and, if possible, contribute to the overall stiffness of the entire chassis.





Looking through the front suspension box and down the transmission tunnel of the finished chassis.

Opposite: The wall thicknesses of the bolt bosses and the stiffening ribs is identical in the firewall to create as smooth a flow as possible for all the stresses. All possible material was removed to save weight. Every blind bolt (a bolt without a nut on the other side) was painted after it was properly torqued. The plate that makes the top of the footbox is 1 inch thick to minimize pedal flex under extreme braking.

## MAIN FRAME RAILS

The word impossible is not in my dictionary.

Napoleon Bonaparte



The main frame rails just as they are starting to be assembled.

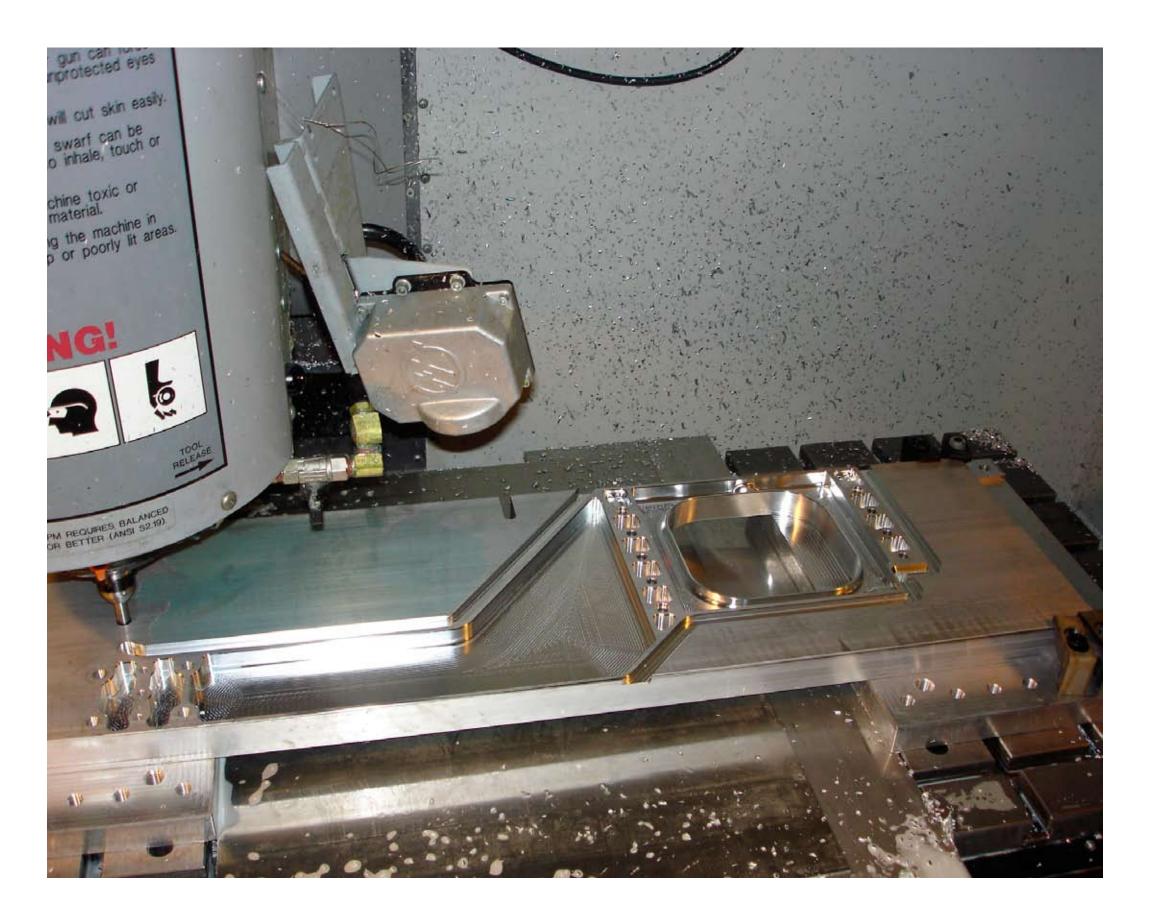


The main frame rails were first blanked out of a 1 1/2 inch x 4 foot x 12 foot plate of aluminum.



The main chassis rails had to be made on a large CNC mill we purchased for this project. Even so, the main frame rails were much longer than the machine area, so we had to hang the ends out of the machine. Machining the main frame rails was extremely labor intensive. They were so long they

had to be machined in 12 separate operations for each frame rail. It was very difficult to hold the tolerances over the 8 foot length of each of the main frame rails. As you can see from "Sandwich's" smile, he did an incredible job of blending the sections. The blends are almost invisible.



Because the main frame rails were so long, we made a special tool to go into a drilled hole in the unused portion of the plate to positively locate the plate. Then we programmed the mill to plunge the tool into the hole. The clamps were then loosened,

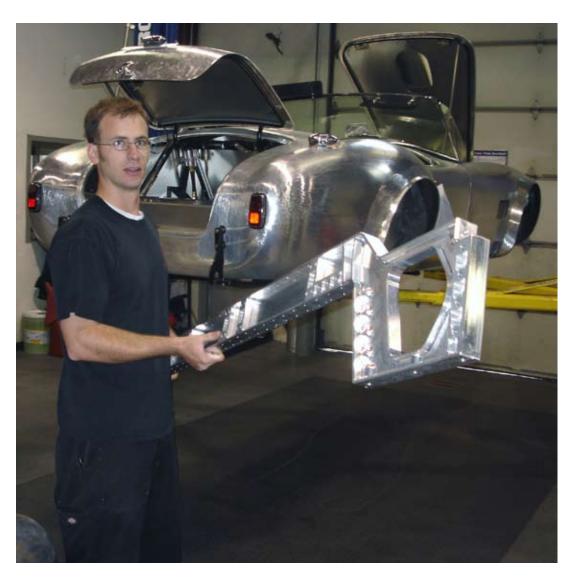
and the mill was commanded to move to the new position. The spindle head held the plate in place while the table slid to the new position. We then clamped the main frame rails down again and repeated the process 12 times for each side.



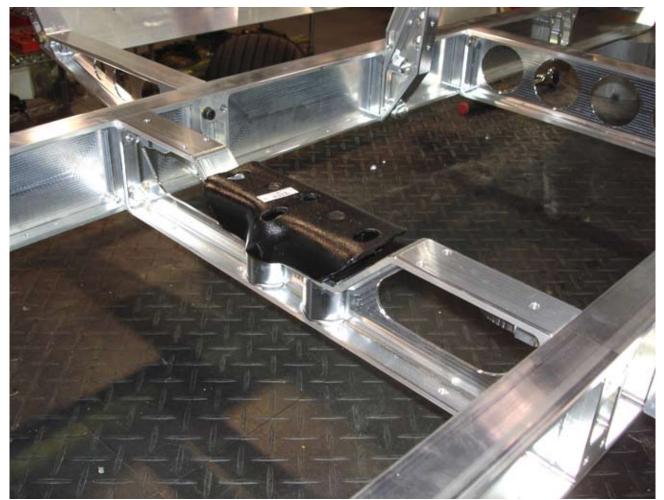
Closeup detail of the main frame rails.



Sandwich deburring the main frame rails after the first operation. Any burrs will throw the plate out of alignment when it is put back into the fixture for the remaining operations—causing significant error over the 8 foot span of the rails.





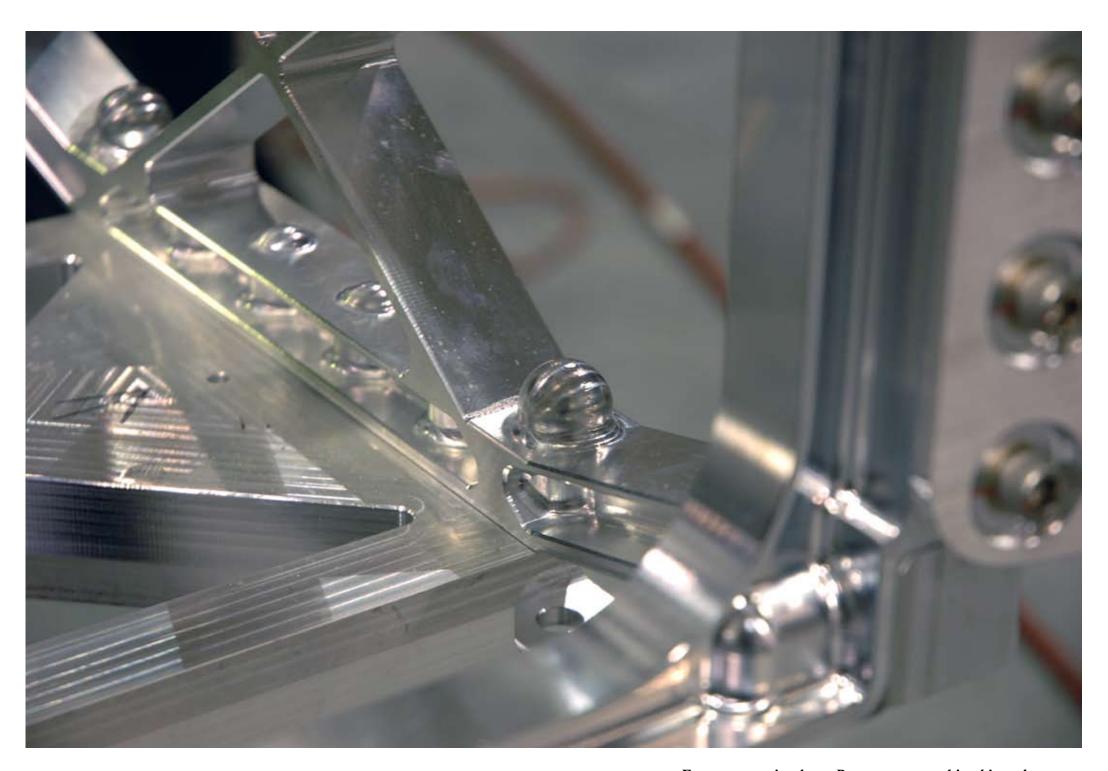


After the chassis was cleaned, all the water was blown out of the holes. The chassis build started with the assembly of the main rails and cross members. To the left is the transmission mount.

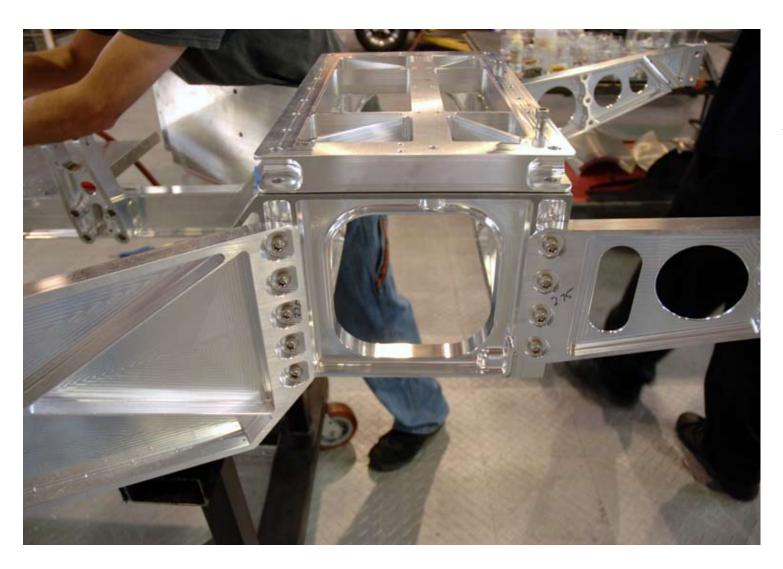
## VERTICAL CHASSIS BUILD

The difference between the impossible and the possible lies in a man's determination.

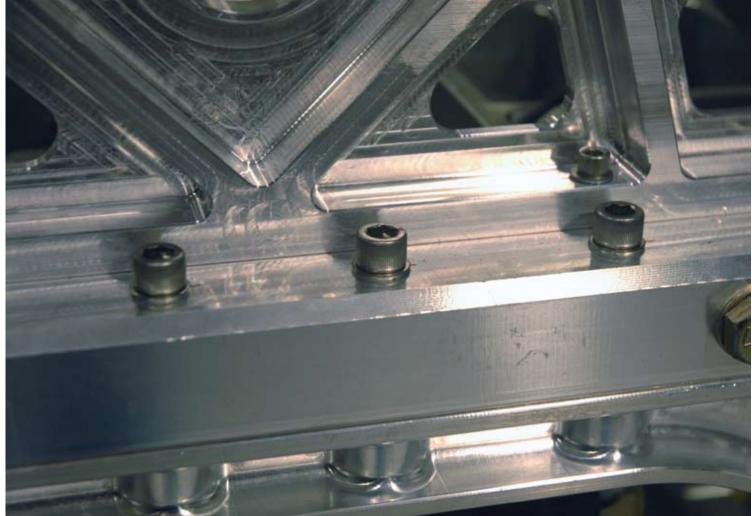
Tommy Lasorda



Front suspension box. Bosses were machined into the chassis wherever a bolt was used. The wall around the bolt was held to 1/4 inch—the same thickness as the webs throughout the chassis.



Front suspension box. The large stiffening plate in the lower left of the picture carries the loads from the front suspension to the footboxes.



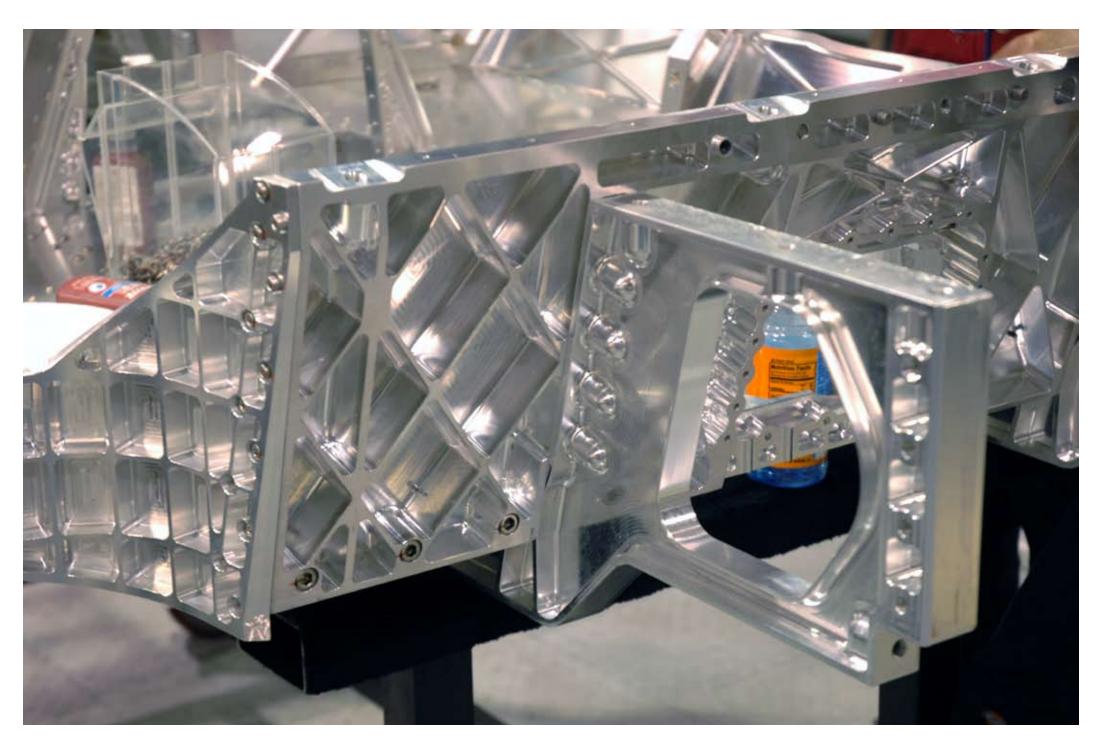
Stainless steel bolts and washers were used throughout the final chassis in all non-critical areas. We used aircraft fasteners in critical suspension applications.



The plate under the door sill was one of the first parts I drew on a piece of paper when we started this project. I knew that to increase chassis stiffness we had to move as much material as possible away from the neutral axis of the chassis. The only place to hide it was in the rockers.



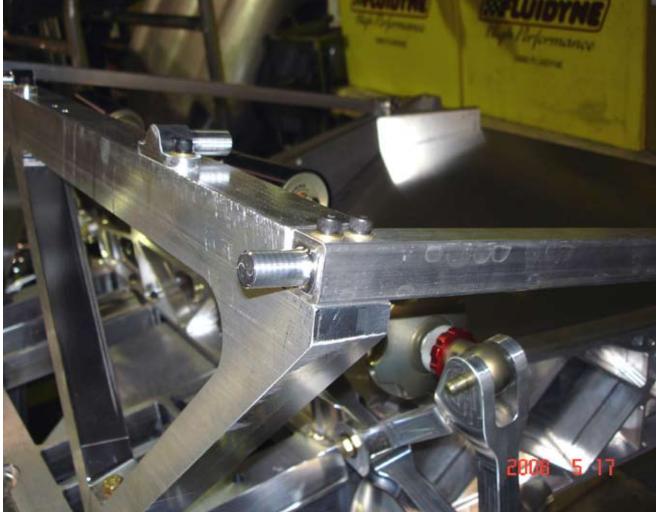
The bowl-shaped tub with tall rocker plates helped to stiffen the chassis.



This is a shot facing forward—looking at the back side of the rear bulkhead. Notice all of the material that was removed to save weight. Also, notice the stainless steel bolts; this is the actual chassis we delivered.



There were thousands of bolts in the car—every one had to be put in by hand and properly torqued.



Many little parts had to be made to join pieces together. This adapter connects the round substructure tubes of the body to the chassis.



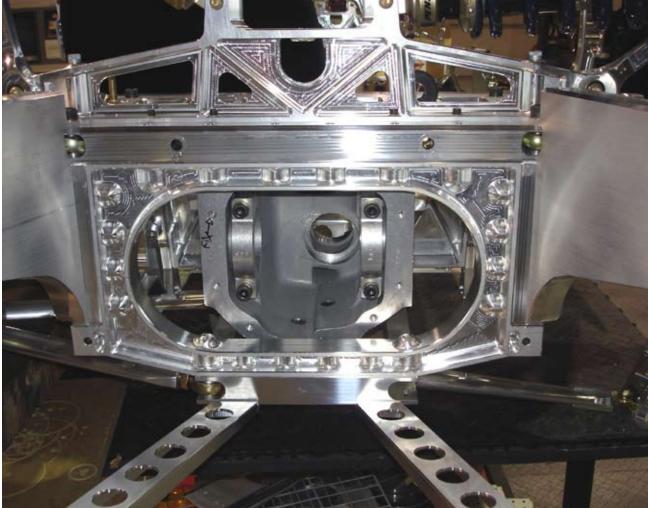
One of the critical parts is the cowl. The doors hinge on the cowl and the windshield bolts to the cowl structure.



Fitting the rear suspension to the chassis.



These large arms form the sides of the trunk and also must support the car when it is picked up by the jack hooks.



Looking from inside the trunk toward the differential. We mounted a bare differential case in the chassis to check clearances. You can also see the gas tank straps coming out just under the differential.



Once the suspension was installed, we ran it through its full range of motion to make sure nothing bound up.



This shot is taken from the rear of the car looking forward. The side arms actually form the sides of the trunk—again, the "sheet metal" was milled directly into the parts to make them as stiff as possible.



The jack hook bolts directly to the chassis.



Many parts had multiple angles machined into them to accommodate the myriad angles of the chassis. This bracket is the rear support for the main "W" bracket that supports the entire rear substructure. The square tube was later welded to the bracket.



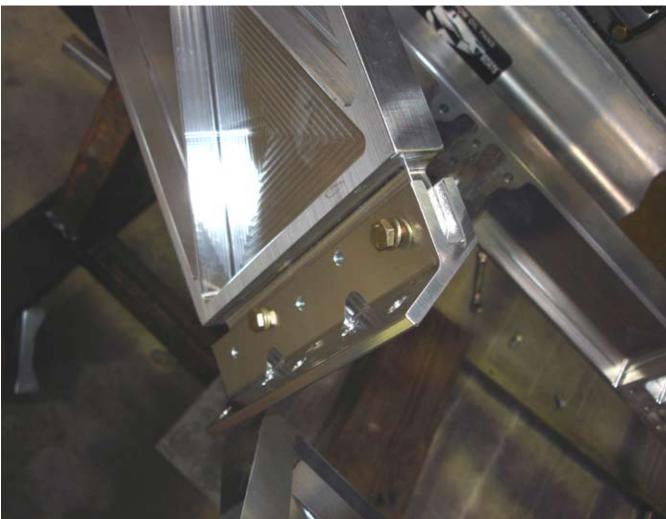
Wherever possible, we made every bracket have multiple functions. This bracket holds the gas tank strap on the bottom. The trunk substructure tubes are welded to the top.



The trunk floor is being installed. The trunk floor bolts to the bottom of the large side arms.



Many different angles and planes came together perfectly to make the front jack hook support.



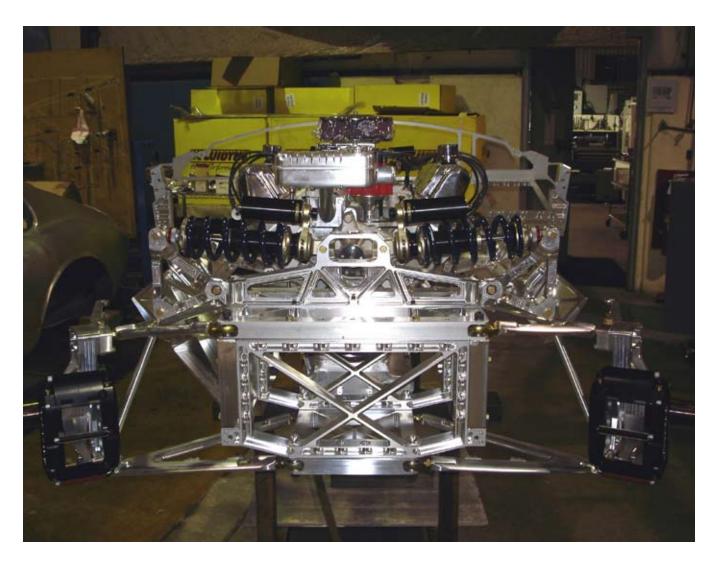
This bracket connects the stiffening side plates from the front suspension box to the footbox.



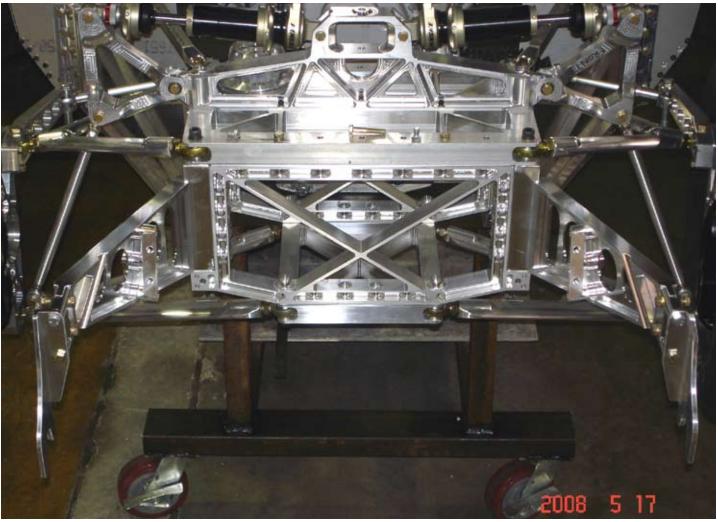
In the center of the chassis, you can see our nod to the original chassis with our billet "down tubes." Just like the original chassis, they connect the cowl structure to the main frame rails. This shot is taken from the rear, looking forward.



Here you can see plates under the door sills and the side cowl pillars that will support the door hinges. This shot is taken from the front—looking rearward.



The front suspension box is heavily gusseted to minimize any flexing as the suspension loads the chassis.



Front chassis arms that support the radiator and front jack hooks.

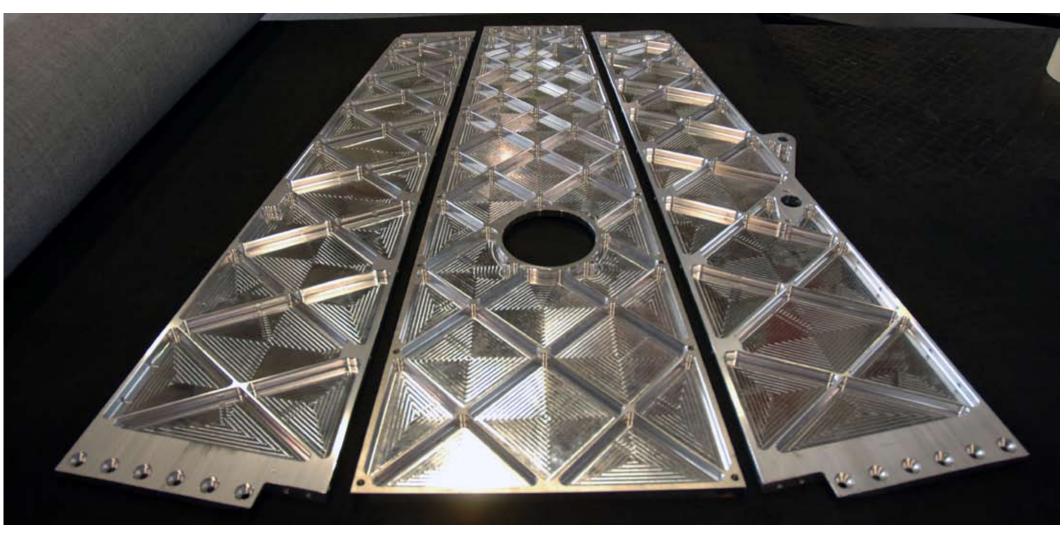
## TUNNEL

One man's "magic" is another man's engineering.

Robert Heinlein

The transmission tunnel is a critical structure affecting the stiffness of the chassis. The tunnel must resist twisting and bending of the chassis. The chassis has to transfer the load from the rear suspension (which moves the car forward) to the front suspension (which steers the car) and vice versa.

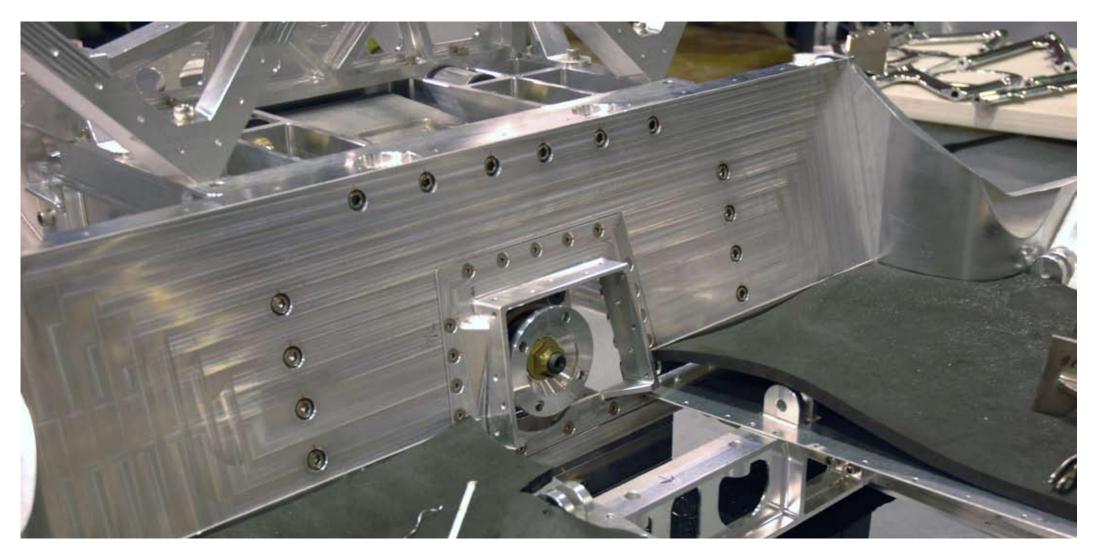
We made the tunnel from 1/2 inch plate to be stiff enough to carry the loads from the rear bulkhead to the footboxes. We hollowed out the inside of the tunnel to remove weight. Finally, the outer surface "sheet metal" of the tunnel was milled directly into the part to make it as light—and stiff—as possible.

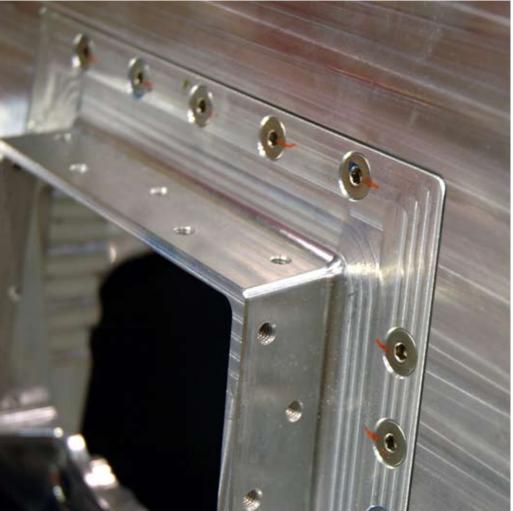


Inside of the tunnel showing the machined pockets to reduce weight.

Every pocket on the inside of the tunnel was filled with individually cut out Aerogel-impregnated insulation. Aerogel is an amazing insulator.

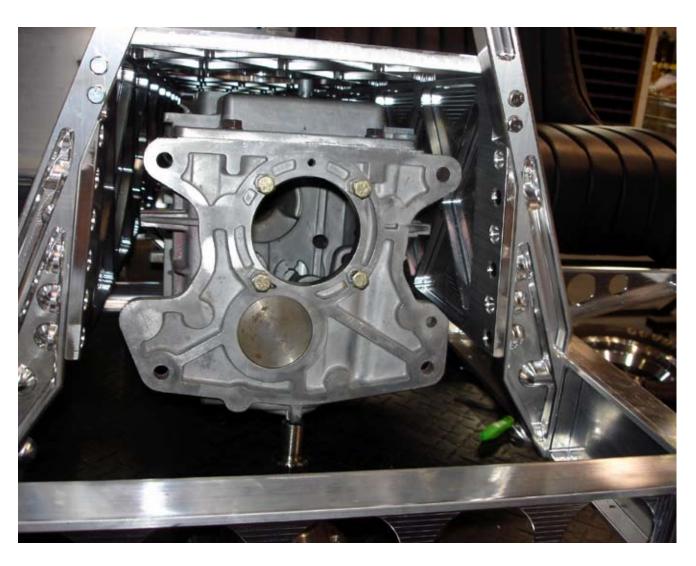






Above: You can see the special plate we machined to attach the tunnel to the rear bulkhead. You can see the round pinion flange of the differential peeking out. The pinion flange is noticeably shifted to one side because the pinion is offset on the differential. All the stainless bolts are countersunk for a nice, clean appearance. Also, notice all the holes in the floor pan. The tunnel bolts to the floor pan to dramatically increase the stiffness of the chassis.

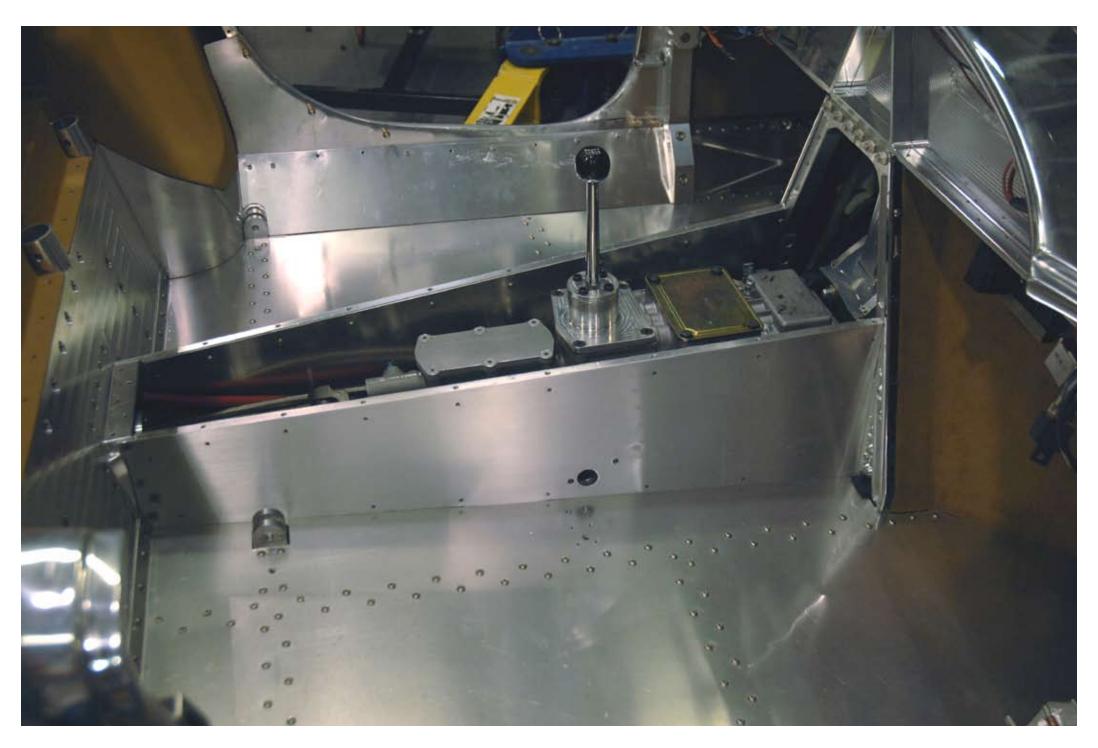
Left: All bolts in the interior were either counter sunk or had a rounded head. The tunnel was not orthogonal to the chassis so all the tunnel parts required multiple setups and fixtures to get the bolt holes at the right angles.



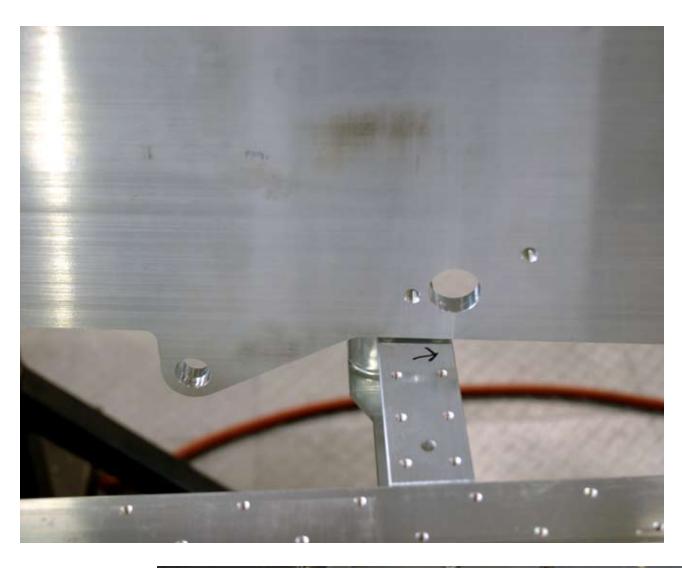
To make the tunnel look right (and not intrude on the driver) we inclined the sides inboard. We had to design braces to carry the load from the tunnel to the footboxes. We made the tunnel fit as tightly as possible around the transmission to give the interior as much room as possible.

Below: The rear of the tunnel bolts directly to the rear bulkhead.



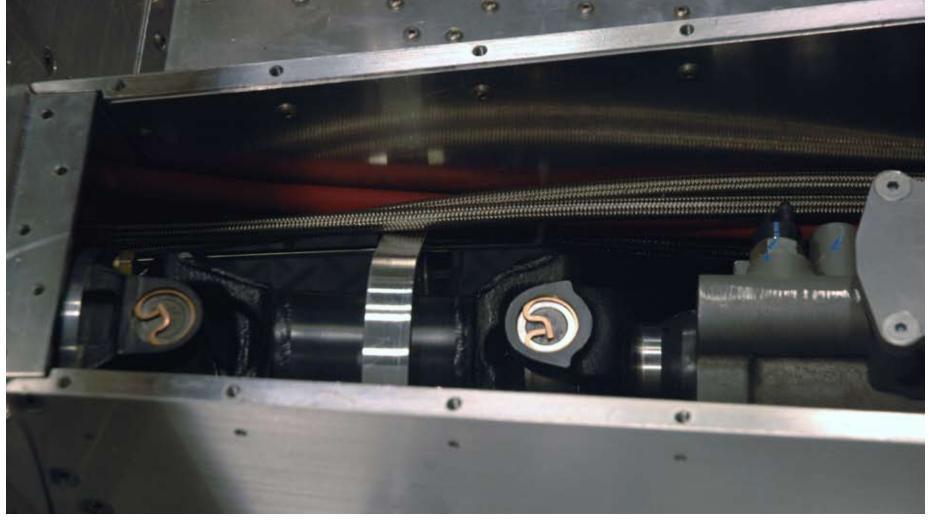


It is critical to connect the rear bulkhead to the footboxes to make the structure as stiff as possible. On the inside of the tunnel, we covered the Aerogel with a sheet of aluminum.



The small gap between the tunnel and the main chassis is supposed to be there. The floor pans have not been installed yet. Notice that the emergency brake mounting structure was machined directly into the tunnel plate so we could save weight.

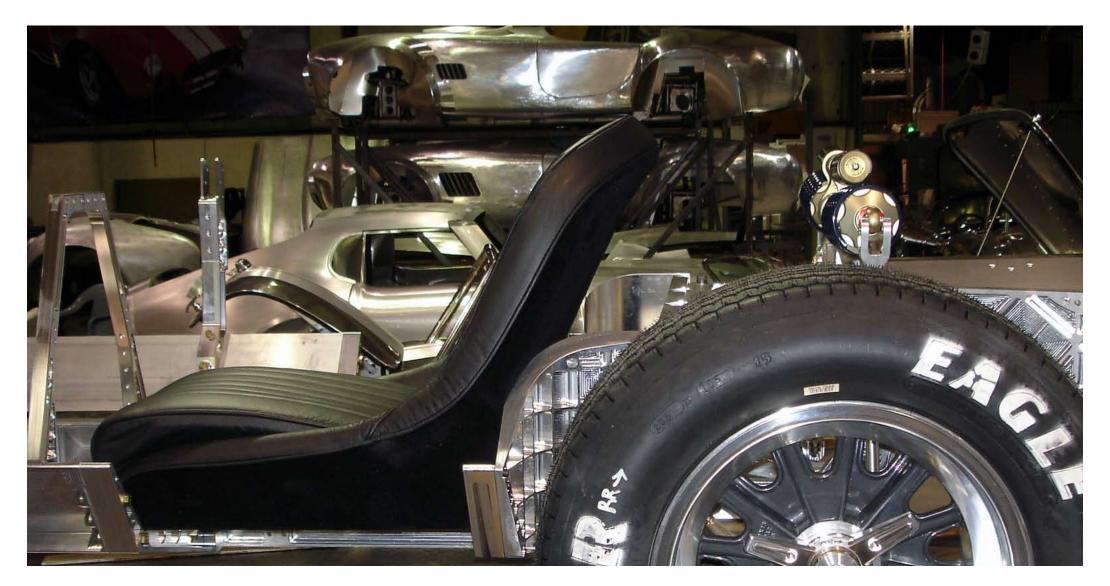
Below: The drive shaft is extremely short in the car because the engine was moved back by 6 inches so we could enhance the weight distribution of the chassis. Also, notice the billet drive shaft safety loop surrounding the drive shaft.



## **REAR WHEEL WELL**

We will either find a way—or make one.

Hannibal



Notice that the driver's head is actually behind the leading edge of the rear wheel.

The most efficient way to carry suspension loads forward from the rear suspension is with a straight rear bulkhead that completely spans the width of the vehicle. In fact, most race cars are designed this way. On the original Cobra, however, the wheel base (the distance from the center of the front wheel to the center of the rear wheel) is only 90 inches. The distance is so short,

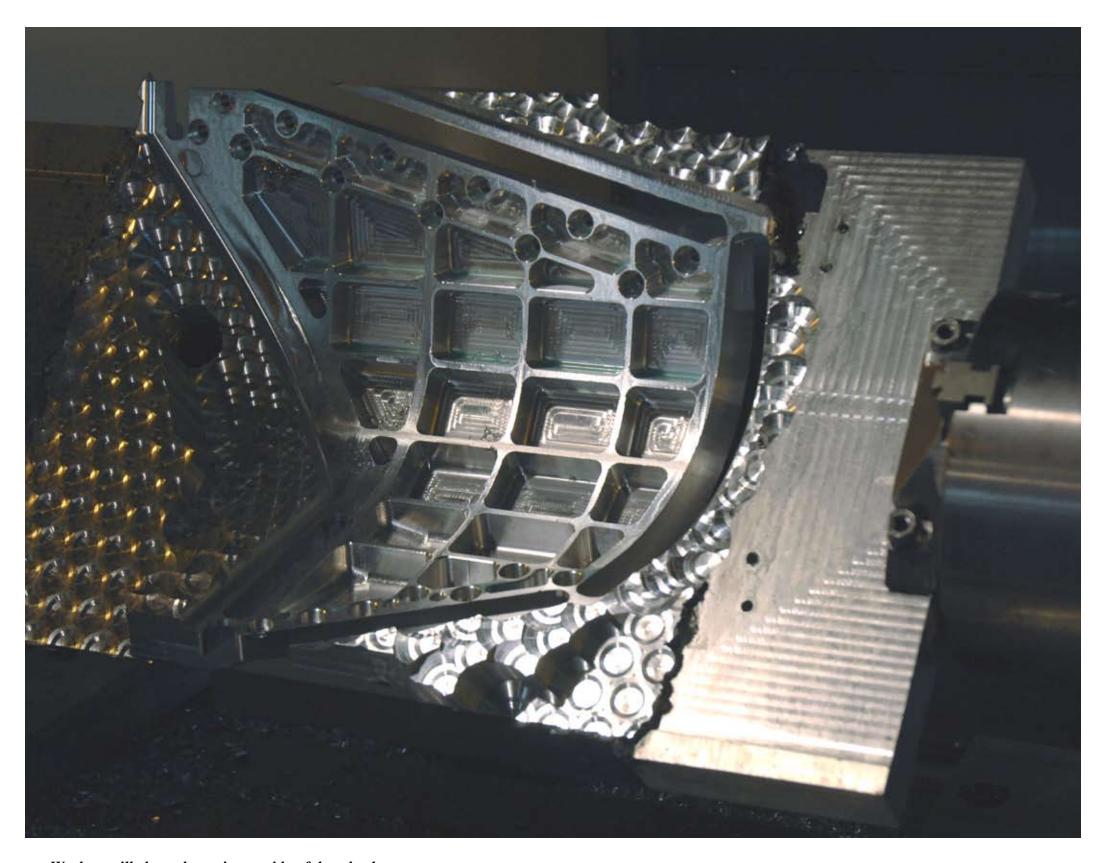
in fact, the leading edge of the rear tire is forward of the driver's head. We had to feed the loads from the rear suspension around the rear wheels and then behind the seats before we could then feed them forward to the front suspension. This presented some extreme challenges to our design team. We had to come up with something clean, compact, stiff, and light.



We began by cutting in half a 147-pound cylindrical billet of aluminum, 12 inches in diameter and 13 inches long.



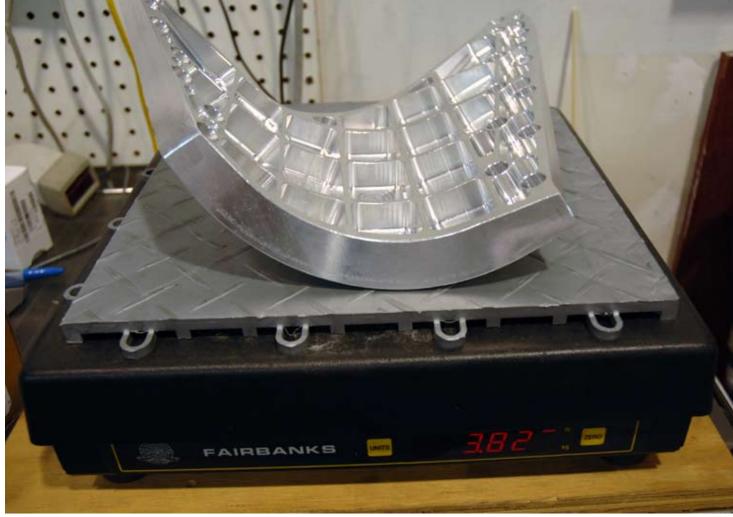
We welded some "wings" on the ends so we could hold onto the billet—they were cut off in the milling process.



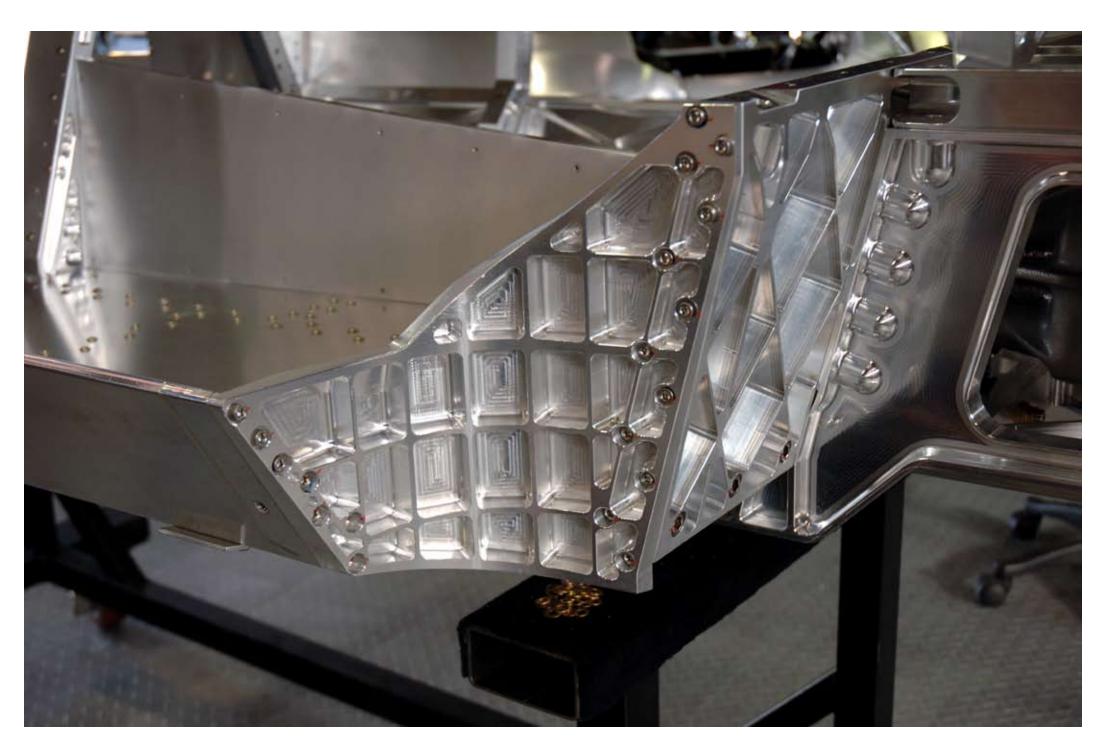
We then milled out the entire outside of the wheel well. The part rotates as it is being machined. This is the tire side.

This is the side of the wheel well that faces the cockpit—behind the seat.

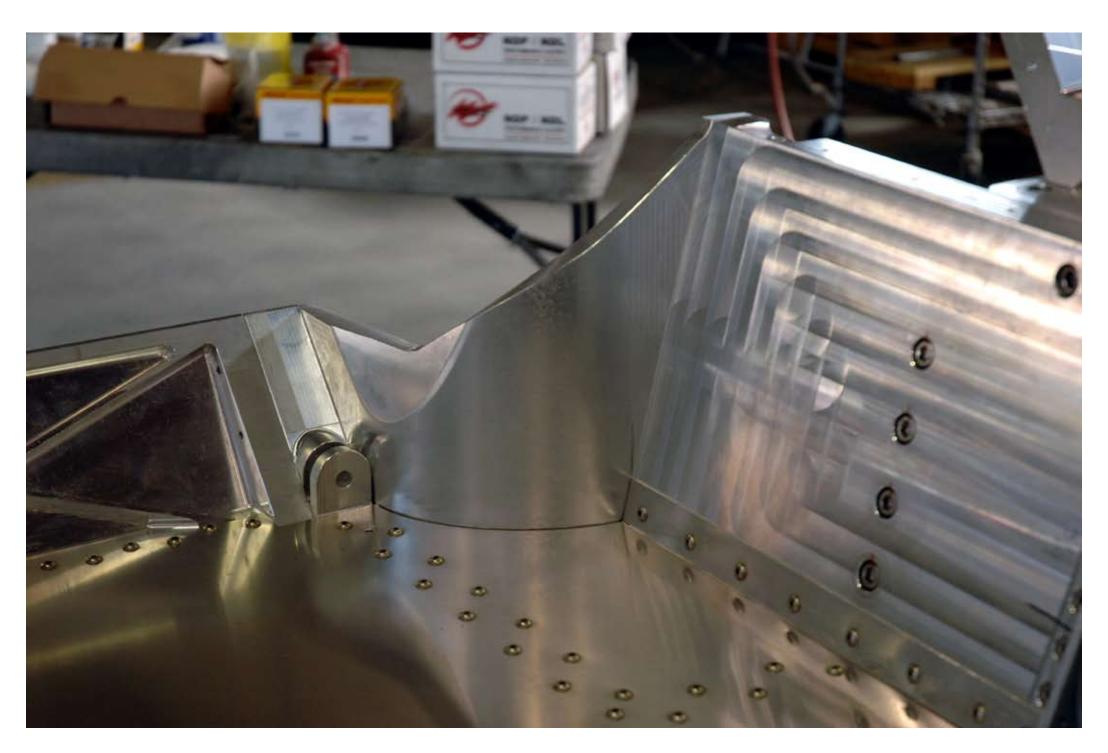




The finished wheel well weighs a scant 3.82 pounds.



The finished wheel well bolted into place. This completed the tub that ties the rear suspension to the front suspension, making the structure very stiff. The rear bulkhead the wheel well is bolted to is 1 1/2 inches thick.

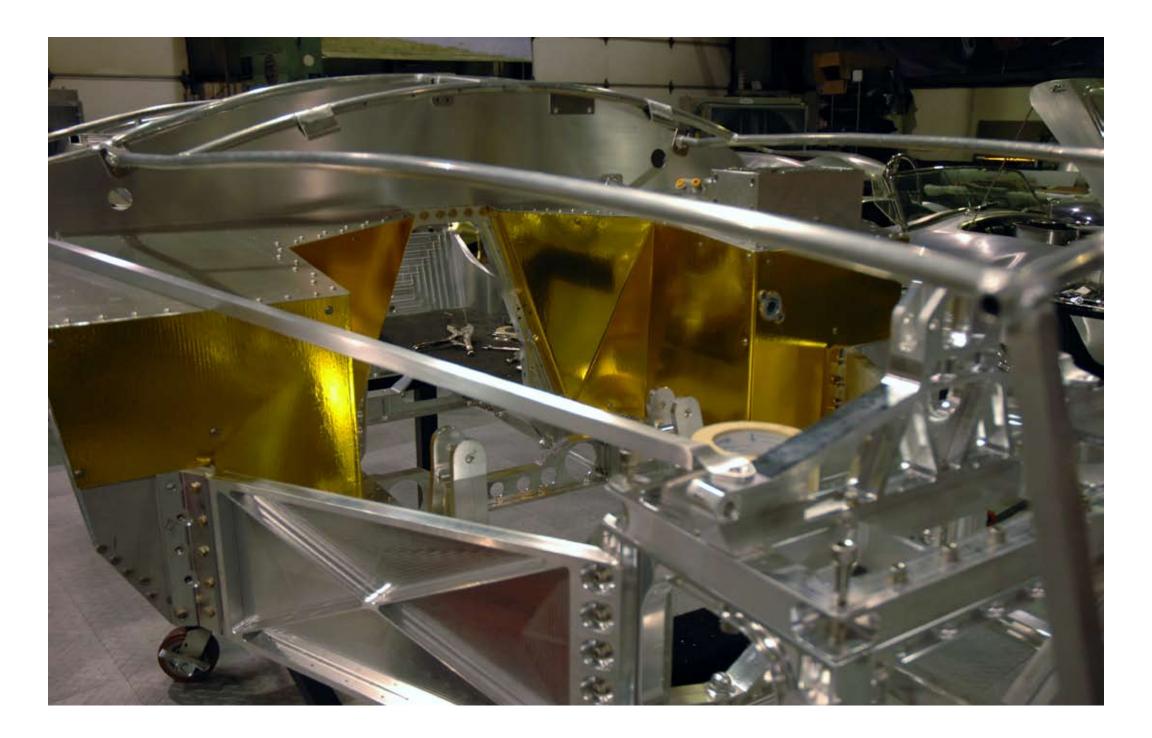


The inside of the wheel well as seen from the cockpit. From here it is easier to see how the wheel well connects the rear bulkhead (on the right) to the plate under the door (on the left), which forms the sides of the "tub." By raising up the sides of the "tub," we were able to make the structure stiffer—much like a bowl is stiffer than a plate.

## **FOOTBOXES**

Everything is theoretically impossible, until it is done.

Robert Heinlein



In an original Cobra, the footboxes are not stressed. For this car, the footboxes have to perform many, varied functions. They are critical to connecting the loads from the front suspension to the rear suspension—through the chassis. Our objective was to transfer all these loads around the huge engine right in the middle of the car as efficiently as possible.

Heat from the exhaust pipes on the driver's feet is a problem in an original Cobra. To combat the heat, we looked to the very latest in aerospace material science. Our first line of defense is the Kevlar-

backed gold foil you see here in the picture—identical to what is used in F1 race cars and the McLaren F1. This foil is extremely light and reflects approximately 80% of the heat radiated from the pipes. Behind the gold foil is a polished stainless steel backing plate. Stainless steel has the lowest coefficient of thermal conductivity (heat passes through it very slowly) of almost any metal. Behind our stainless shields is a layer of Aerogel—the substance with the lowest thermal conductivity known. All these modifications completely tamed the intense heat from the pipes.



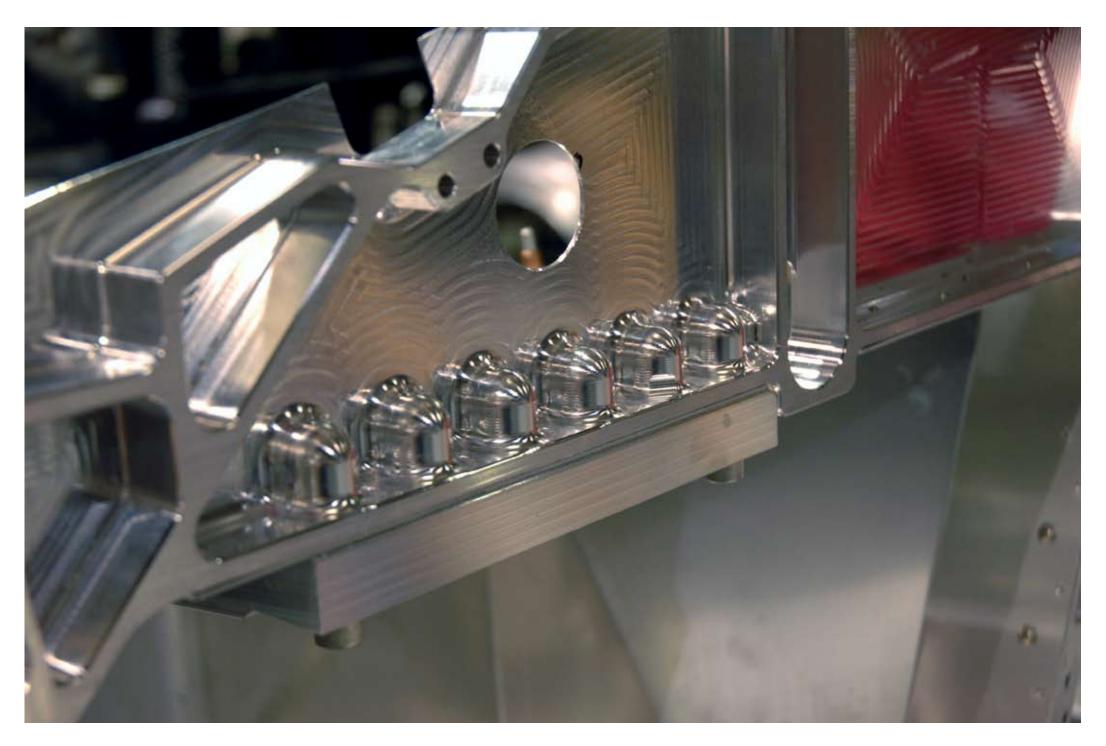
Many holes in the floor pans were at off angles that could not be drilled and tapped by the CNC mill—they were done by hand on the prototype.



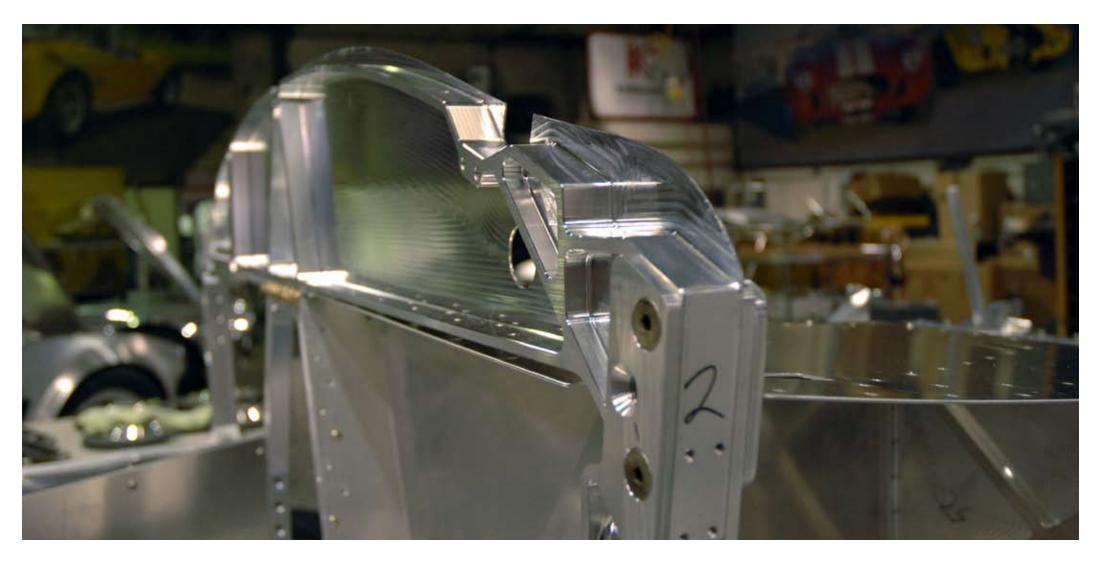
We made special fixture plates to do the drilling and tapping at the correct angles in the delivered car.

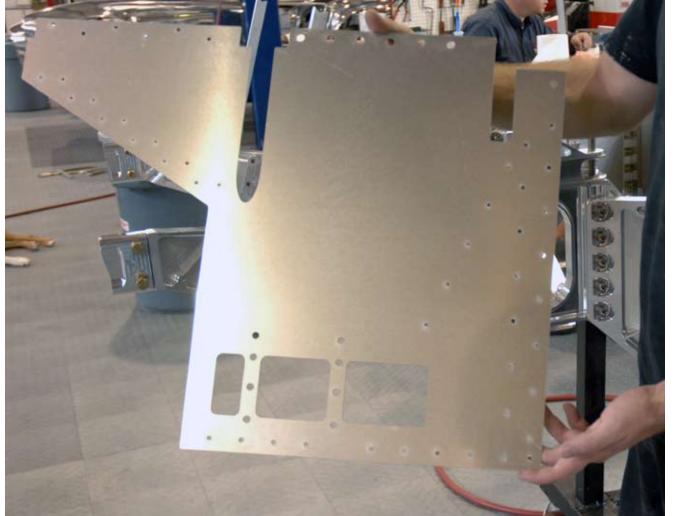


The door sill plate does not sit orthogonal to most of the chassis as it had to be tilted to extend up as far as possible under the door. The further we could extend it up, the stiffer the chassis would be. The door sill plate is extremely long. It ties the rear wheel well all the way to the front of the footbox.



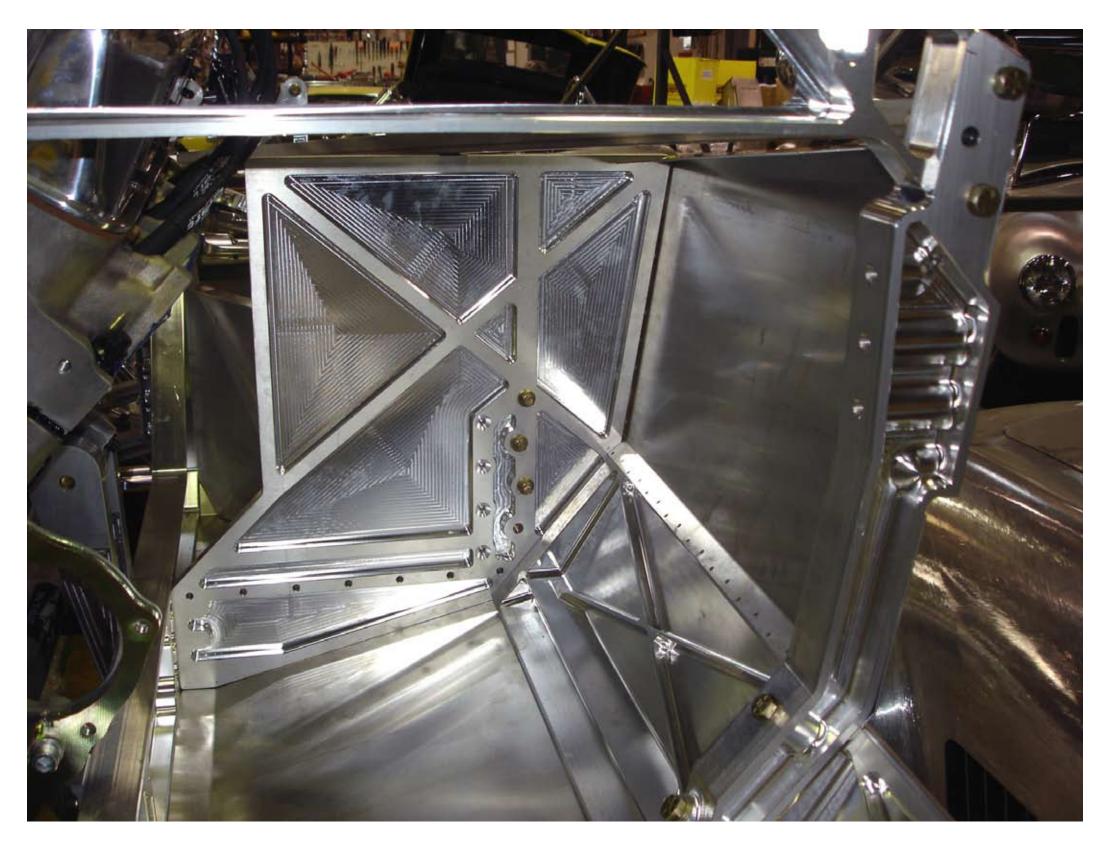
From this angle, you can see we milled the firewall "sheet metal" right into the part to save weight and increase the stiffness. Notice we even removed all the material around the bolt threads to reduce weight as much as possible. The hole is for the wiring harness. The large 1 inch plate (shown with 2 out of 6 bolts) supports the brake, clutch, and accelerator pedal assembly. The plate is thick to minimize brake pedal flex.





Above: The firewall was milled from a solid 1 inch plate of aluminum. It is extremely stiff—to minimize cowl shake.

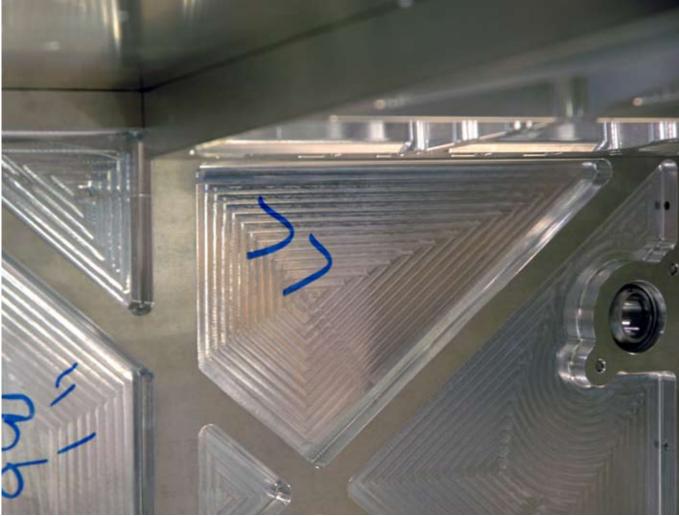
Here you can see some of the complexity of the footboxes. Notice the long cut-out for the steering shaft and the three holes in the bottom for the pedals.



A look inside the passenger footbox during assembly. The footboxes are complicated structures that have to "hug" the huge 482 cubic inch motor. The front of the footboxes is made from 1/2 inch plate because it has to carry significant loads to and from the front suspension box.



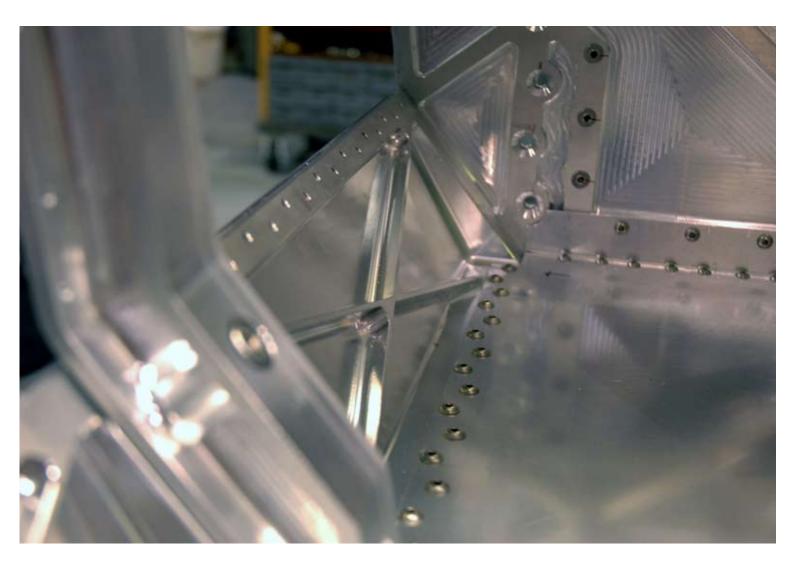
We took our original brake and clutch pedal and hung them upside down in the prototype chassis to evaluate pedal position. If you look closely, you can see the "KIRKHAM" lettering is upside down.



The footboxes were extraordinarily complex. The front plate of the driver's footbox alone had 77 holes drilled and tapped—in nine different planes.



The outer panel of the driver's footbox being fitted on the prototype.



Inside of the driver's footbox on the final car we delivered to Larry. We used button head bolts throughout the interior to prevent the driver from snagging his feet.



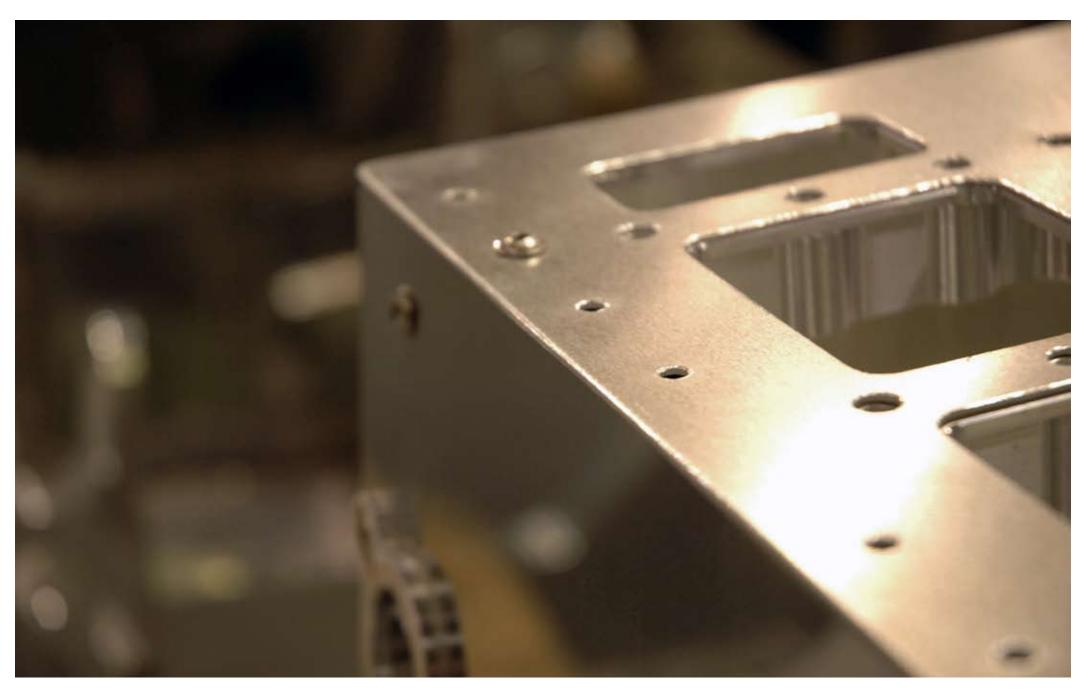
The inside of the passenger box as it was being assembled in the prototype.



The floor pans also provide a tremendous amount of stiffness to the chassis.

Below: Here the bowl shape of the tub is coming together. From this angle, you can see how far the rear wheel intrudes into the cockpit. Also, if you look carefully, you can see the seat belt mounting points sticking up out of the floor.







Above: Extreme care was taken during the design and execution of all the parts in the car. Notice that all the panels and holes line up perfectly with each other.

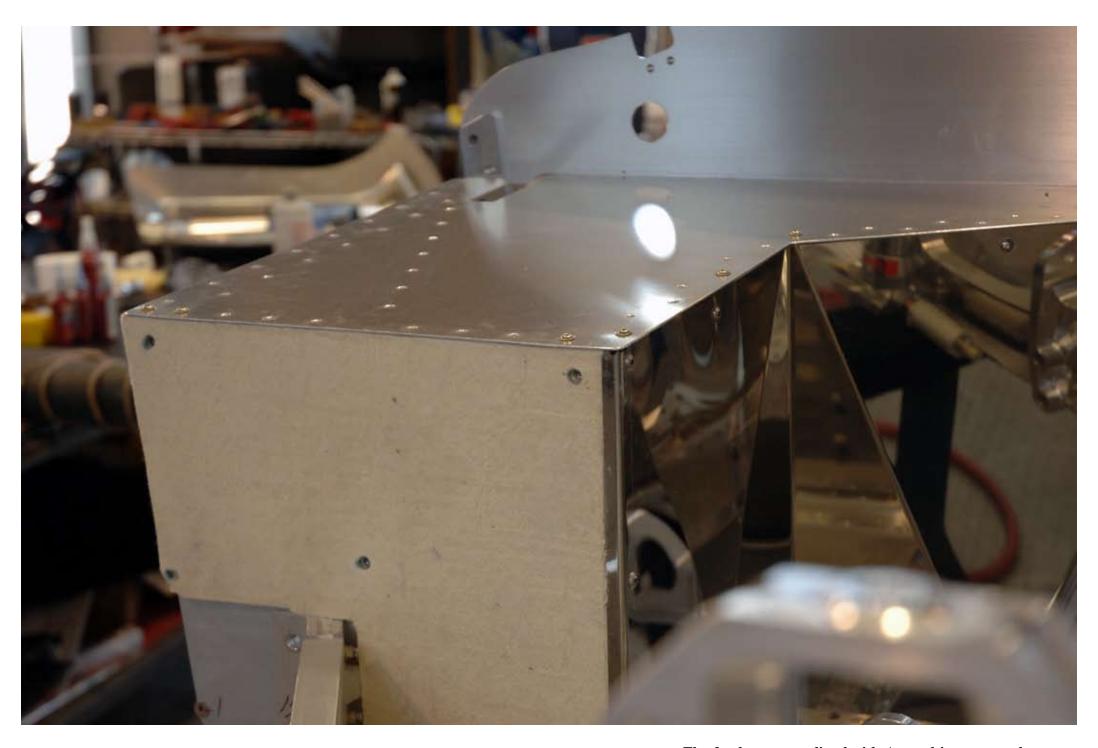
All sheet metal was cut out on our OMAX water jet cutter. A water jet uses a 50,000 psi pressure jet of water mixed with fine garnet to cut metal (and almost anything else). The precision of the machine is incredible.



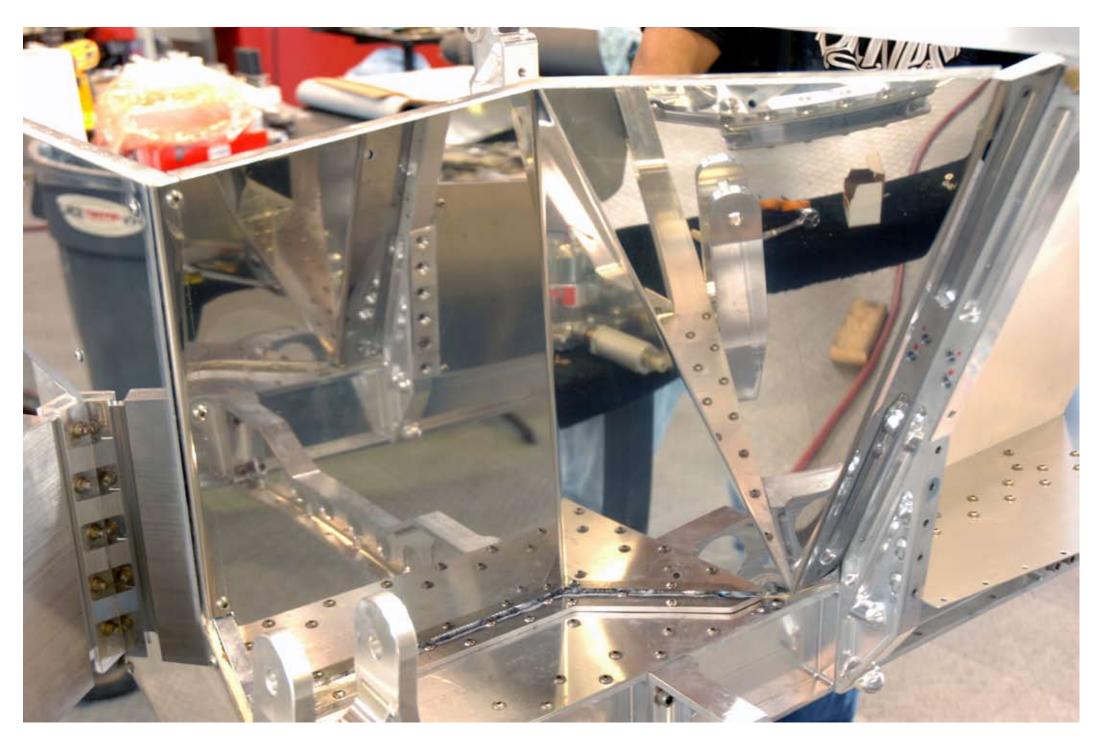
The driver's footbox supports the steering column. If the steering system is not adequately secured to the chassis, it can cause wheel shake. We used a bearing to hold the shaft firmly. Also, the steering shaft—indeed the entire steering shaft system—is made from stainless steel to prevent corrosion over time.



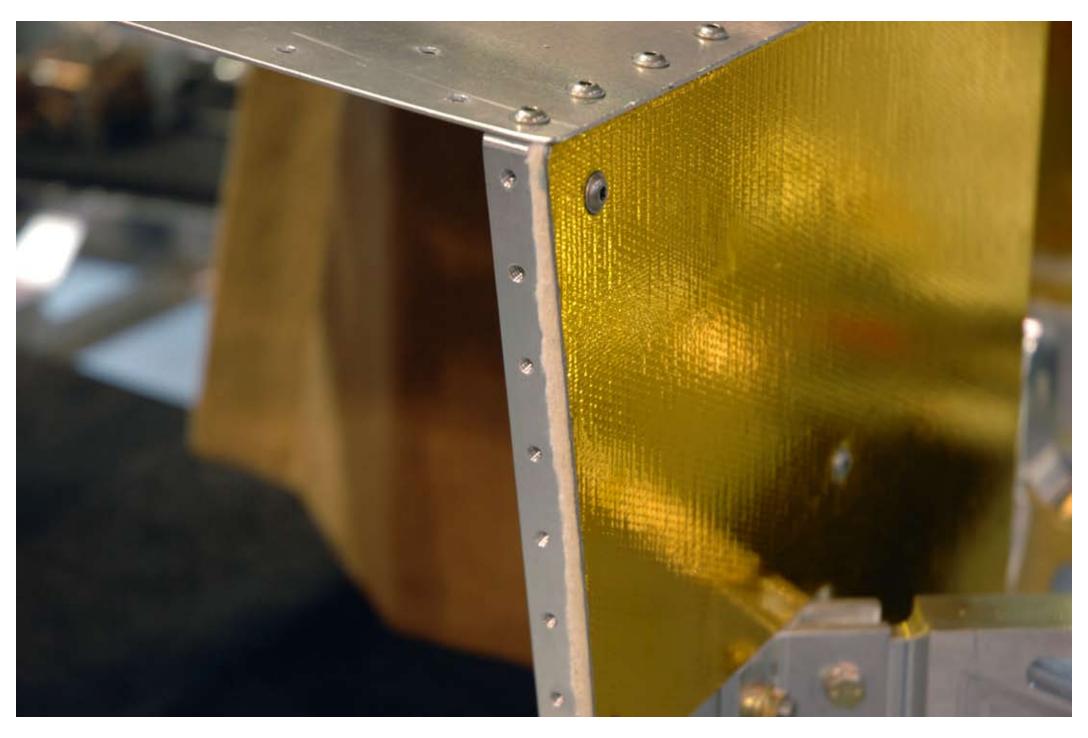
This plate transmits loads from the front suspension box to the footboxes.



The footboxes were lined with Aerogel-impregnated insulation. Aerogel is the lightest material known. It also has the lowest coefficient of thermal conductivity known. It is used in the Space Shuttle, Formula 1, and other demanding situations where temperatures must be controlled.



The Aerogel matting covered by a polished stainless steel heat shield. Stainless steel has the lowest coefficient of thermal transfer of all common metals.



Last, we covered the stainless steel with a Kevlar backed gold foil that reflects 80% of the heat radiated by the exhaust tubes. The foil uses a special high-temperature glue to fix it to a stainless heat shield. Also, notice that the top of the footbox and the front plate are not orthogonal to each other.

## UNDERCARRIAGE

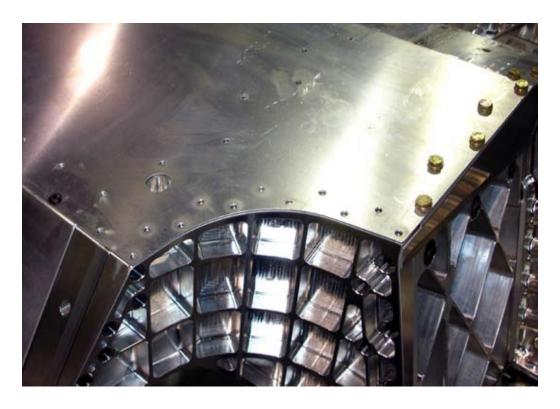
Opportunity is missed by most people because it is dressed in overalls and looks like work.

Thomas Edison

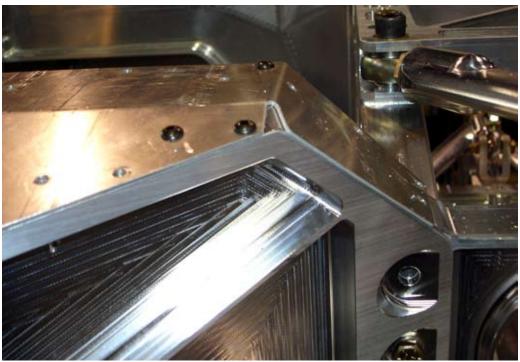


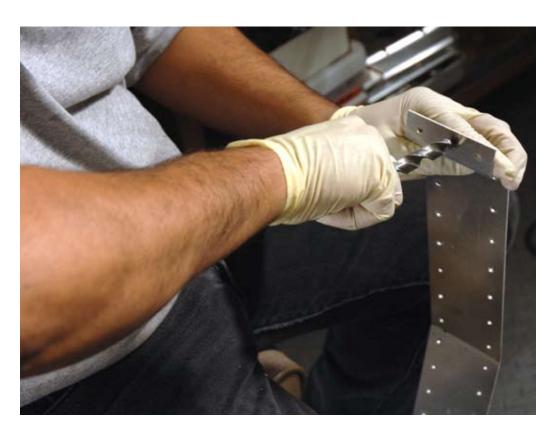
We designed the chassis similar to the construction of an airplane, with longerons and a stressed skin. The main chassis rails on the car are analogous to the longerons in the wings of an airplane. The floorpans, under body trays, and belly

pan are analogous to the stressed outer skin of a wing. Everything—including bolt holes—was laid out in CAD, and the sheet metal was cut with our water jet. We used steel bolts in the above prototype chassis. In Larry's car we used stainless steel bolts.



The edges of the sheet metal line up exactly with the machined parts. Many holes had to line up on several different parts—all at different angles after being bent in a press brake. The chassis is upside-down (on a rotisserie) in these two pictures.



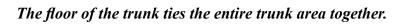


Every hole and edge in the entire car (a few thousand) was deburred on both sides—by hand if necessary.



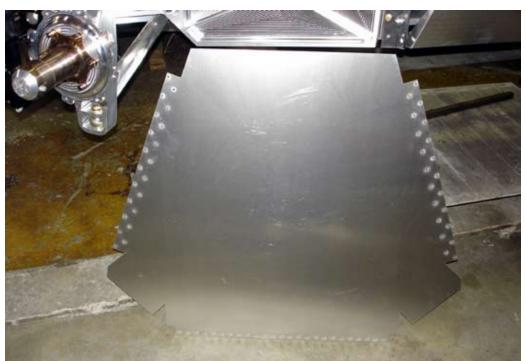


The belly pan has 87 holes that tie together 9 individual parts.





The under chassis pans provide a great amount of stiffness to the chassis as well.

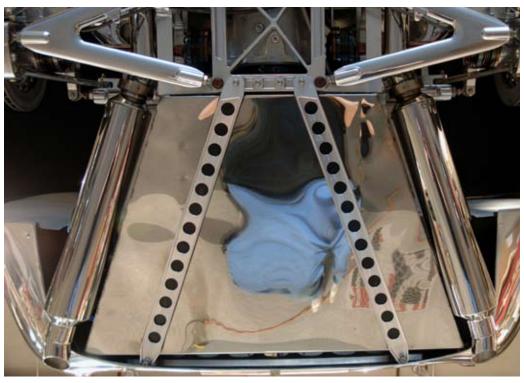




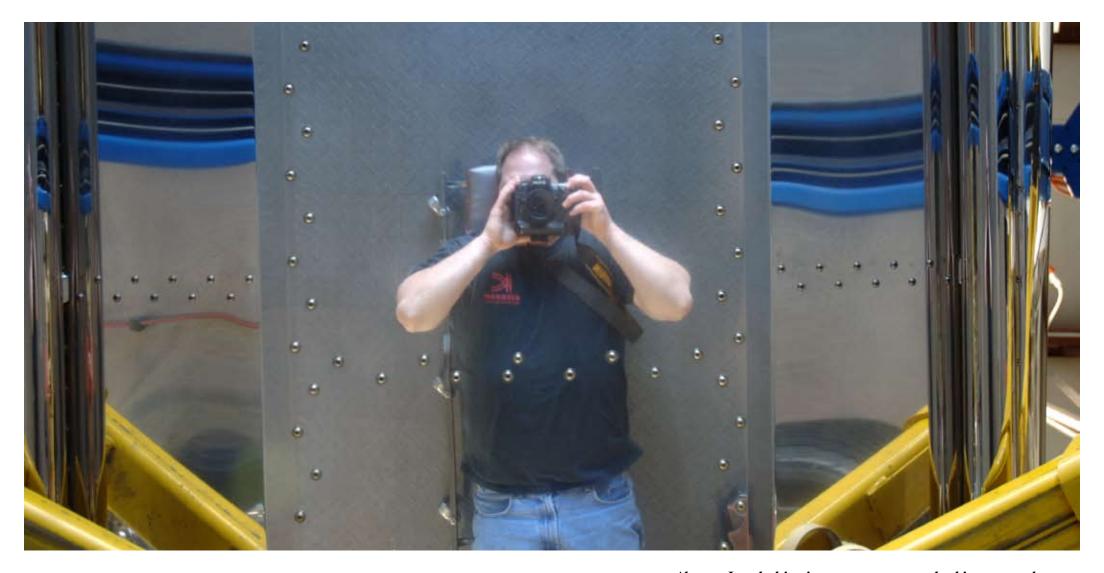
Above: A view of the final chassis during construction with no belly pans on the car. The chassis is upsidedown (on a rotisserie) in this picture.



The side belly pan bolts all the way down the bottom of the rocker. The bolt holes are staggered to reduce the bending moment on the bolts, thus loading the bolts in almost pure tension and shear. The belly pans tie the rear suspension box and main frame rails all the way to the front of the footboxes.



The gas tank is made from stainless steel to prevent rust as condensation forms in the tank over time. We made the gas tank fill up as much of the rear under carriage as possible to minimize turbulence under the car and to act as a diffuser.



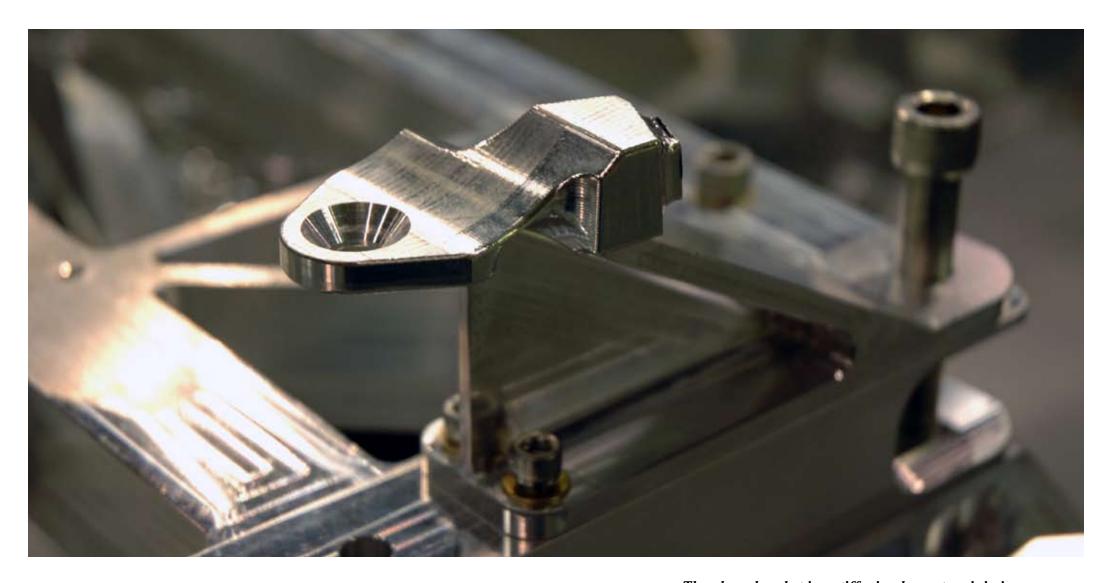
Above: I took this picture on a creeper looking up as the car was on our lift. The main reason for the dramatically improved stiffness of the chassis over an original Cobra is because we stressed both the floor and belly pans. We used button-head bolts to make the entire underside of the chassis as smooth as possible, thus reducing aerodynamic drag. The belly pans were polished to a mirror finish. The center belly pan looks grey and textured because it is reflecting the grey Race Deck diamond plate texturing of the shop floor.



## **MACHINING**

Trifles make perfection, and perfection is no trifle.

Michelangelo



The above bracket is a stiffening brace to minimize flex of the front shock tower. We machined a dish into the top of the bracket for shock clearance. Notice the tapered hole for a flat head bolt. The area is too tight for anything else.

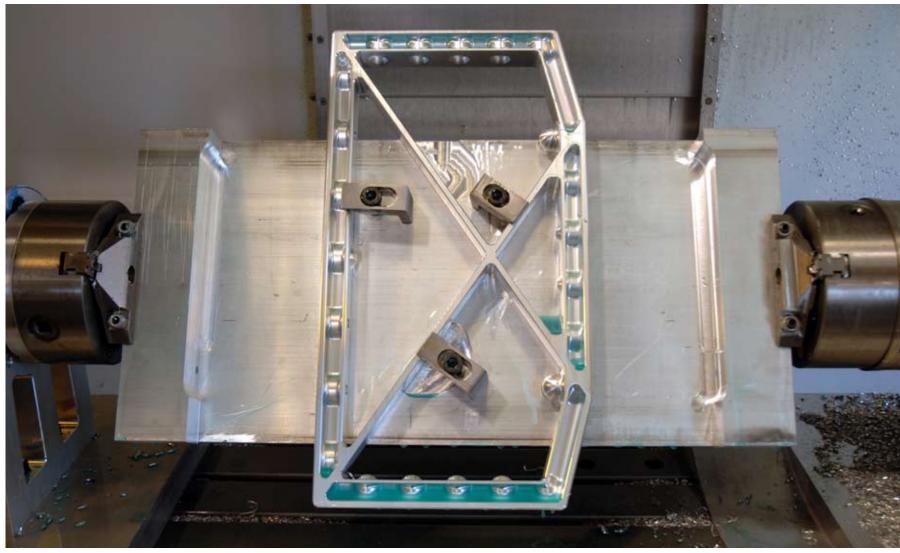


Left trunk brace. It has many different angles on it that had to be fixtured so they could be machined accurately. The "sheet metal" was milled directly into this part to save weight.



We made many different fixture plates to machine all the different angles in the parts.

Below: A fixture plate in action on the 4th axis. The 4th axis is for spinning the part around. Many parts, like this one, had to be machined on all six sides—requiring many operations.





Left: The cross member in the top of the photo is recessed for the transmission mount. The cross member in the lower part of the photo goes in front of the differential. This design was later superseded when we made provisions for a drive shaft safety loop. The small, tapped holes in the bottoms of both cross members are for mounting the belly pans.

Below: The prototype's front jack hook arms that support the jack hooks and radiator—this piece too was later superseded with a lighter design.







Every part on the chassis was pressure washed before assembly so the Loctite would have a clean surface to stick to. Every fastener in the car that went into a blind hole was secured with Loctite.

Differential upper mounts.



This is part of the cross member behind the passenger's seat. The sharp triangular area is where the door sill plate bolts in.



The motor mounts are a fail-safe design with through bolts to prevent the engine from breaking loose if the urethane should ever fail. The motor mounts are also quite stout with 1/2 inch walls. We have seen too many motor mounts fail in accidents.



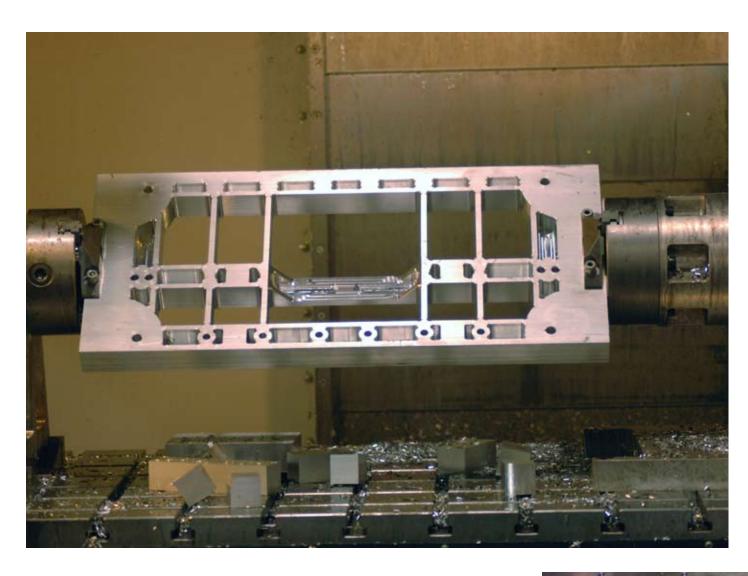
The motor mounts are designed to spread the load over the entire frame rail by tying the top and bottom of the main rail together.



The steering arm (at the top of the upright) was designed to capture the outer tie rod in double shear to eliminate any cantilever loads on the tie rod bolt. The steering arm was later superseded by a stiffer part. The big bore in the center of the upright is for the large Lexus bearing we now use in all our cars. The bearing is rated for a life of 300,000 kilometers—in cars with twice the mass.



The front upright was a challenge to design with everything we wanted. Notice the upper and lower ball joints are captured in double shear. The upright is hollow to allow airflow for brake cooling. The brake caliper side of the upright is not hollow because it has to feed braking loads into the wheel bearing to stop the car.



This is the top plate of the rear suspension box during manufacturing. The cut out in the center enables the plate to clear the top of the differential.

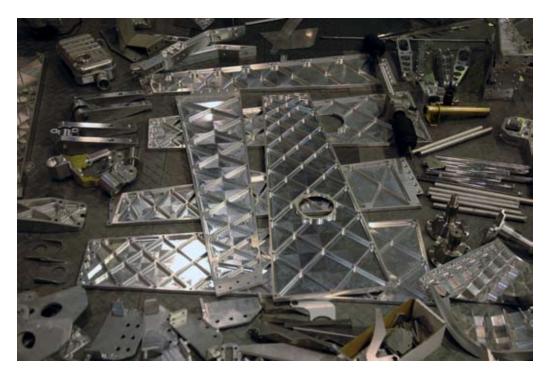
Right, top of photo: The upper bracket that connects the rear upper control arm to the rear upright. Notice the rod ends are captured in double shear. Bottom of photo: The special bolts are the pins for the upper and lower control arms. The threaded sleeve nuts are designed with external right-hand threads and internal left-hand threads to allow alignment adjustments without disconnecting the control arms. The parts are made from 17-4 PH stainless steel.

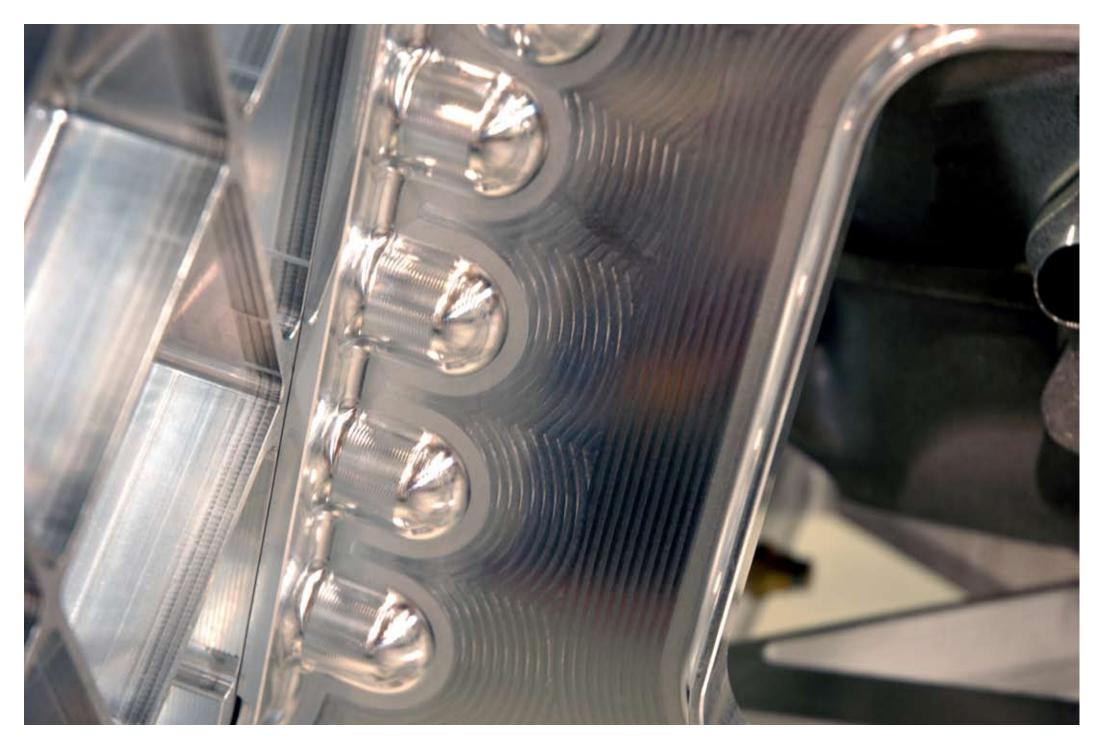






Many parts fell by the wayside as we constantly refined the car during the prototype phase. Any time we came up with a better idea, we immediately redesigned and manufactured a new part.





Closeup of the rear bulkhead and main frame rail junction.

On the opposite page is the evidence of many hours of work that could be considered "tuition." We learned from every abandoned part. Some were made several times—until we were satisfied with them. Even

the CNC tool paths were programmed so the milling marks left by the cutters in the parts would be beautiful. We wanted every part to be a sculptural and engineering masterpiece.



Even tiny machining marks make tiny stress risers in a part. The stresses on the above control arm are concentrated where the two legs of the control arm join. We conscientiously programmed the tool paths to run around the control arm in long sweeping arcs—without stopping—to minimize any stress risers from the machining process.



All machined parts had deburring passes painstakingly programmed into the sweeps and curves of the CNC milling paths for consistency and beauty. This is the rear shock rocker.

## HALF SHAFTS

If I have seen farther it is by standing on the shoulders of Giants.

Isaac Newton



Throughout the years we have been fortunate to have many of the world's best car designers, panel beaters, engineers, race car drivers, and others at the peak of the automotive world share their methods and knowledge with us. One of our customers, Kenny Hill of Metalore, makes the constant velocity (CV) joints, hubs, and axles for most of the F1, Indy, and Lemans teams. He also has made many of the critically machined

parts on satellites and the space shuttle. There is no finer automotive engineer, designer, or machinist on earth than Kenny Hill. He has shown us his secrets of machining and engineering design on some of the most critical and highly stressed parts on the world's highest performance cars. We used Kenny's CV joints in our 1/2 shafts and employed many of his machining and design secrets during the creation of this car.





10 silicon nitride balls weigh 0.14 pounds



Porsche 6 steel balls weigh 0.74 pounds

Among the things that make Metalore's CV's so light (and extraordinarily strong) are the ceramic silicon nitride balls—straight out of aircraft jet turbine engines. There are ten balls in a Metalore CV joint. Metalore uses ten balls because they have a much greater contact area than typical Porsche six ball CV's. Ten balls are able to spread the load around the joint very evenly, as there are ten contact patches instead of six. Silicon nitride balls are exceptionally light—less than 1/5 the weight of Porsche CV balls-and yet the Metalore joint can withstand over 800 horsepower for an entire season of racing. The constant velocity joints take a tremendous beating in any high-performance car. The Porsche CV's probably wouldn't last a single lap in an F1 machine.



Metalore joint weighs just 2.76 pounds.



Porsche production CV weighs 5.16 pounds.



Metalore CV caps are made from the same hard material as the actual joint so they will not yield under high stress.

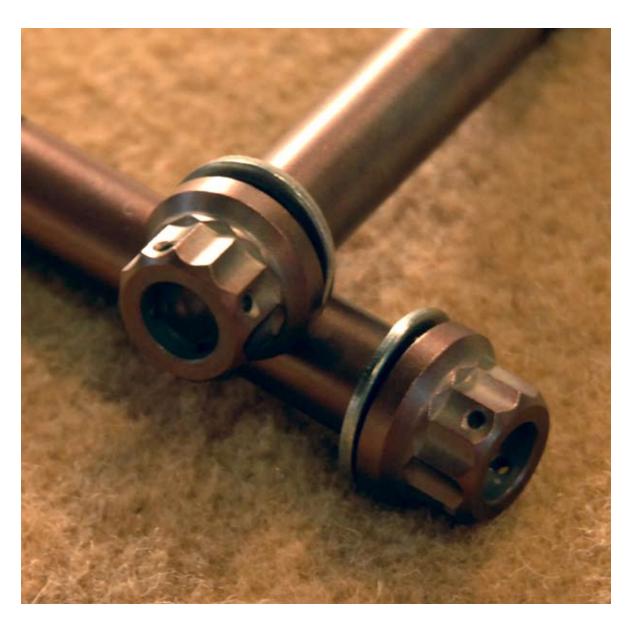


The Metalore CV is almost 1/2 the weight of the Porsche production CV. There are four CV's per car, so this is a savings of almost 10 pounds of rotational mass and 5 pounds of unsprung mass. The more rotational mass, the more difficult it is to accelerate a car. The more unsprung mass, the more difficult it is to control the contact patch of the tire as the wheel moves up and down. Also, the Metalore CV's were "finned" to reduce the rotational mass to a minimum and to help dissipate heat.

Above left is the back cup on the Metalore CV. The cup is made from the same hard material as the CV joint so it will not yield under the CV bolts. Production CV cups are notoriously soft and squish out under severe use. If the cup material yields under the constant vibration and loads the CV's are under, the

distance the bolt clamps will get smaller and the bolt will lose all preload, vibrate, and eventually back out. As production joint covers are stamped, they have to use a softer, formable steel. Such soft material in a high-performance application will eventually squish out under the extreme loads applied by the axles. The shiny button in the middle of the Metalore cover above is an axle stop to prevent the CV joint from bottoming out on (and damaging) the ceramic balls.

Above right is the CV top cup on the Metalore CV. Again, it is made from the same hard material as the CV joint and the rear cover. The boots are made from silicon for extreme temperature use. If you look closely at the inside of the boot, you can see it has a labyrinth seal to keep the grease from spewing out at the high rpms found on F1 car axles.



Left: CV joint bolts. The heads are dimpled to reduce weight and drilled for the extremely important safety wire.

Below: The area directly under the head of the bolt is highly stressed from the large change in cross-sectional area at that point. This area needs to have a generous radius to prevent three F's on the CV report card—fatigue, fracture, and failure.





High-performance bolts require high-performance washers. These washers are chamfered on one side to clear the radius under the head of the bolt. It does no good to use a normal, sharp-edged washer to cut under the head of the bolt and create a stress riser at its most vulnerable point.



This is the "spreader washer" used on normal production CV joints. They try to spread out the load of the bolt to prevent the soft stamped seal cups on production CV's from squishing out. They are a very cheap, unreliable band-aid that does not address the root of the problem—the soft cups squishing out and causing bolts to loosen and fail.



A standard Porsche axle design is on the right. We patterned our axle after the Metalore axle on the left.

The Metalore F1 axle is on the left, and the Porsche production type axle is on the right. On the Porsche shaft, notice the raised shoulder on the inboard end of the spline. This shoulder is designed to stop the CV joint as it is pressed onto the axle—bad idea. The highest stress concentration in the axle is exactly in this area with the shoulder.

In a production axle, the minor diameter of the spline is the smallest diameter on the shaft—so it is the weakest spot in the axle. The largest diameter of the axle is that raised shoulder—so it is the strongest spot in the axle. So, in the production axle, the weakest part of the axle twists right next to the strongest part of the axle. Therefore, the point of HIGHEST stress is right

at the junction of the weakest part of the axle to the strongest part of the axle because all the forces have to be resolved over an extremely short distance. You might as well write "BREAK HERE" at the shoulder on the Porsche shaft because that is surely where it will break.

Consider the Metalore axle on the left in this picture. The minor diameter of the splines is only 0.025 inches bigger than the major diameter of the rest of the shaft. As such, the "weakest" part of the axle is the full distance between the minor diameter of the splines on either end of the shaft. Therefore, the shaft can resolve all the twisting forces over the entire length of the shaft—greatly enhancing its fatigue life.



Metalore CV joint axle retaining clips.

This is the ingenious axle retaining device Metalore uses. In the upper half of the axle hole, you can see a split ring sitting down in a pocket on the inner race of the CV joint. If you look very carefully, you can see a 45-degree chamfer on the inner edge of the ring. This chamfer seats against the 45-degree chamfer on either end of the splines cut into the axle. The split ring is shown with the chamfer up in this picture so you can see it. When the axle is actually

installed into the inner race of the CV joint, the chamfer faces down against the 45-degree chamfer on the axle splines.

A spiral lock retaining ring (top of the picture) then slips into a groove (just above the split ring) and locks the entire system together so the axle cannot come out. By not holding on to the splines and by not creating a shoulder for the joint to press against, Metalore has minimized all stress risers in the axle.



Hub side "Tulip" for the 1/2 shaft—made from 17-4 PH H900.

To drive the wheels, the 1/2 shaft needs to be splined at both ends. This is the hub side of the 1/2 shaft. The part is machined from a bar of 17-4 PH stainless steel that weighs 36 pounds. The finished part weighs 2.6 pounds. We use 17-4 PH because it is a precipitation hardening steel that does not require quenching to achieve the required hardness for extremely demanding parts. With 17-4 PH, there is no

risk of a micro crack forming during quenching. 17-4 PH has strength comparable to 4340, a nickel-modified, chromoly steel.

4340, however, is extremely prone to corrosion and thus not at all suitable for a street-driven car (unless you like rusty parts). F1 teams don't mind using 4340 as they inspect and change parts frequently, long before rust can form.



1/2 shaft bolts are notorious for backing out. We safety wired all the bolts to eliminate any chance of their backing out. Notice the reflection of the safety wire in the main axle shaft. The axle was polished to a mirror finish to minimize stress risers. The CV boots are made of high-temperature silicon to resist deterioration over time, as the differential can get quite hot under racing conditions. The boot is also very small. Normal, larger, bellows-type boots tend to balloon at high speed. If the balloon gets large enough, it will be cut by anything it rubs against (exhaust, frame, and suspension members) and fling the CV grease away, destroying the joint.

The differential side of the 1/2 shaft is made like a modern 1/2 shaft with a spring clip on the inboard side (small groove at the top of the spline). This allows the removal of the axles out of the differential without taking it completely apart. This "tulip" is also made from 17-4 PH. It is golden colored because it has been heat treated to the H900 condition. H900 is the highest strength condition 17-4 PH can achieve—an astounding ultimate tensile strength of 200,000 psi with a yield of 180,000 psi. For comparison sake, Titanium alloy 6AL-4V (used extensively in the F-22) has an ultimate tensile of 135,000 psi and a yield of 125,000 psi.





Above: The completed 1/2 shaft. We made the axle as long as possible to minimize the angularity the CV's will endure as the suspension moves up and down. The shorter the axle shaft, the more angle the CV joints have to resolve. Under extreme angles, the joints are weak and wear out quickly. You can clearly see in this picture the "finning" of the CV joints to enhance cooling and to reduce unsprung weight.



The 1/2 shaft axle for the prototype car being machined on our 3-axis CNC lathe from 17-4 PH. Notice the special driver so we wouldn't damage the splines.



Left: The drive pins were machined directly into the hubs. This is the lightest possible way to make the hub as it removes all fasteners. F1 began making their hubs this way at the same time we did. It is an extremely difficult machining operation because the tools are quite slender and long.

Right: If you look carefully at 12:00, 4:00, and 8:00 you can see there is a little ledge machined into the hub (also visible in the photo at left). The ledge prevents the rotor from falling behind the hub. The rotor is driven by the outside diameter of the hub, just like an F1 car. The internal splines in the axle drive the hub.





The drive pins are oblong shaped because the top and bottom of the pin cannot contribute to accelerating the wheel. Anything that didn't make the car lighter or go faster was machined off.



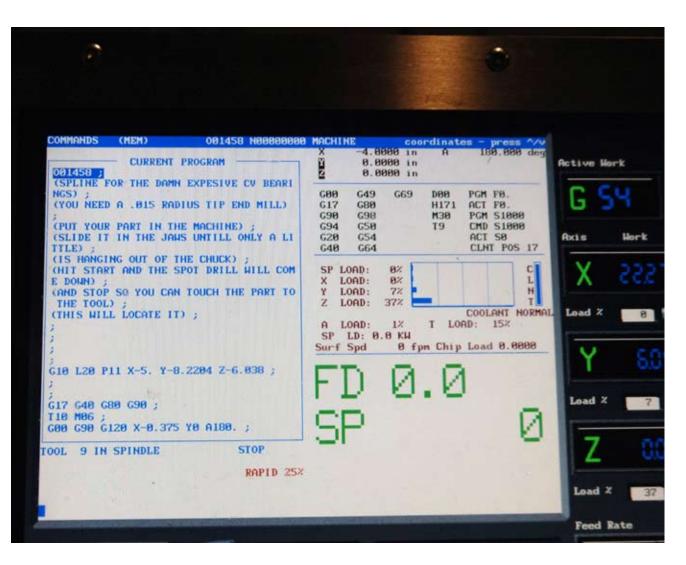
Axle and hub assembly. The bearing has the ID and OD ground to make trial fitting of the assembly easier. It is marked "BAD" so it is not used in production.



Installed 1/2 shaft. The exhaust has to hug the chassis to not interfere with suspension movements.



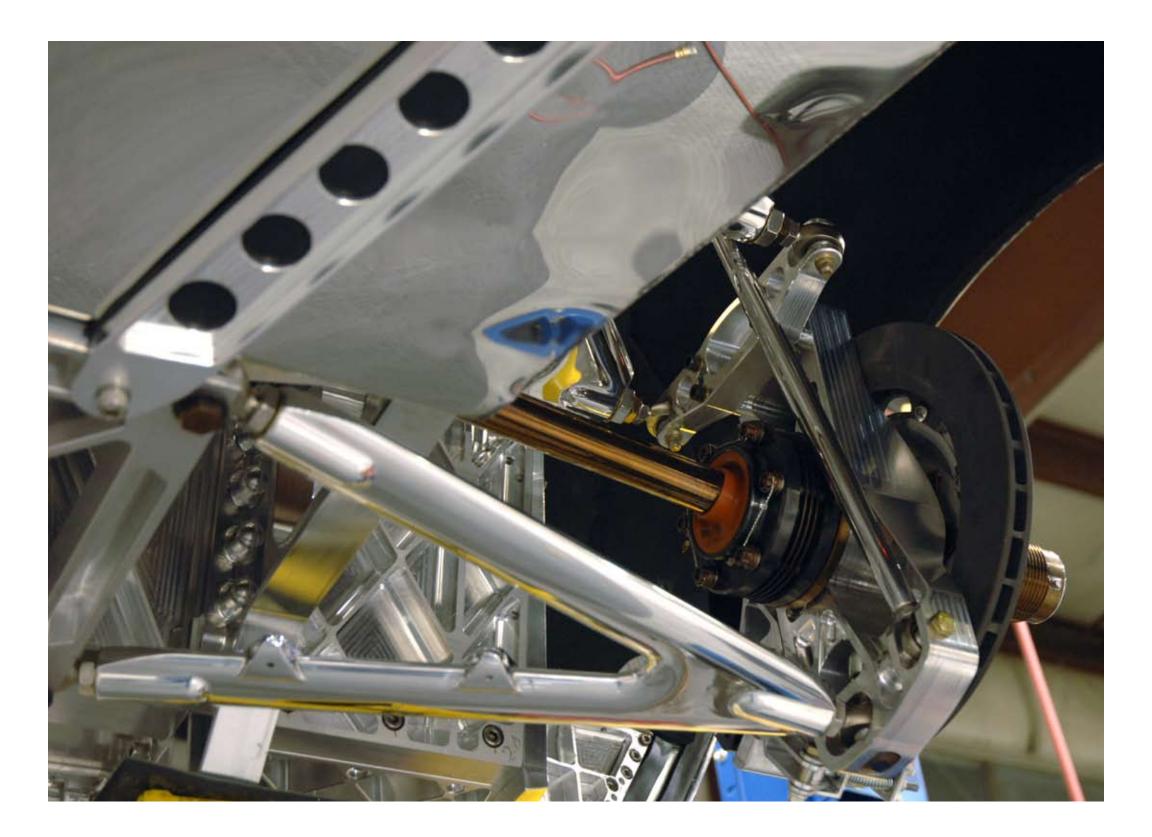
The axles were splined on one of our 4-axis mills.



A little comic relief while we were working with extremely expensive parts. The first line of code says, "SPLINE FOR THE DAMN EXPENSIVE CV BEARINGS."



Using a micrometer to make sure the hub side of the 1/2 shaft has the correct minor diameter.



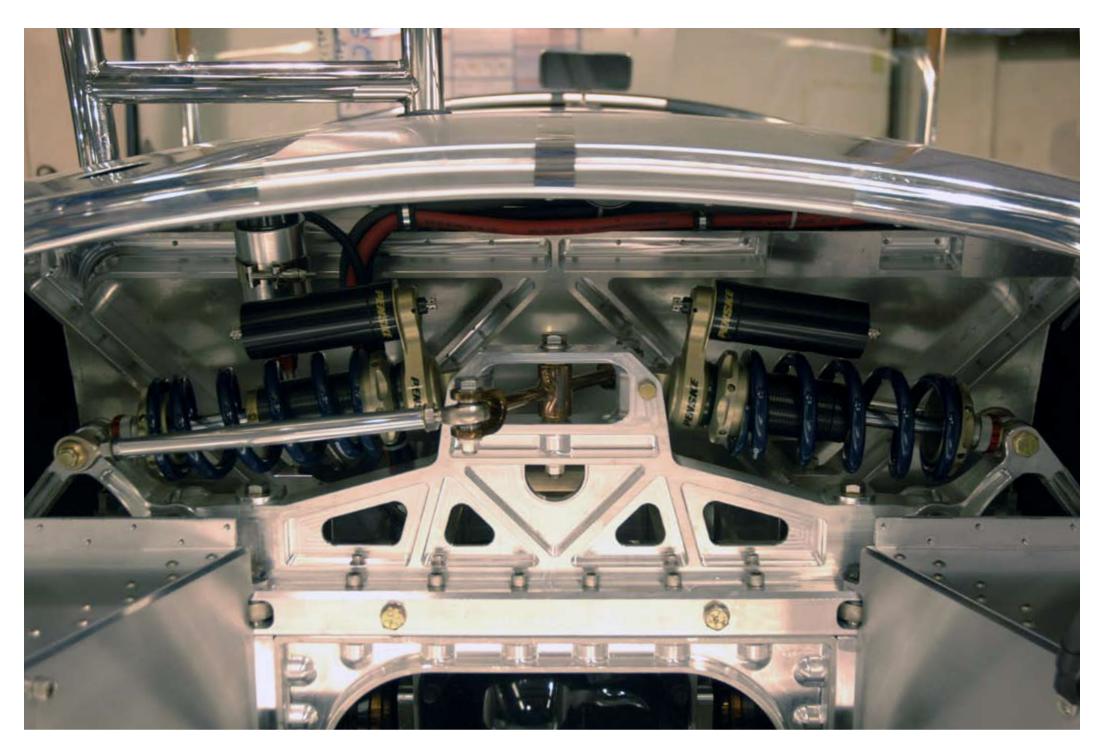
Here you can see the hub side of the installed 1/2 shaft. Of particular interest is the push rod. We made push rod widest in the center, tapering toward the ends. As push rods "push" on the shocks, they want to

buckle in the center (think of standing on a soda can—it fails in the center). By making the push rods wider in the middle, we were able to even out the stresses along the part and reduce its over all weight.

## SUSPENSION

A journey of a thousand miles begins with a single step.

Confucius



Completed rear push-rod suspension.

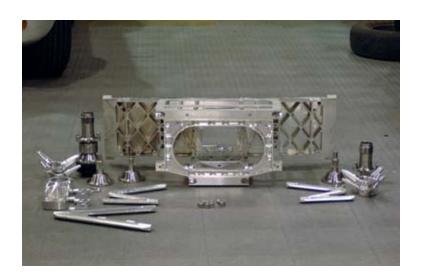
The completed rear push-rod suspension. We chose to use a push-rod suspension so we could adjust the shock travel rate independently of the wheel rate. You want the shock to move as much as possible when the wheel moves. The farther a shock moves, the easier it is to control the wheel because the shock has

more "time" for the valving to work. Here you can also clearly see the sway bar we designed. The sway bar is designed such that it works progressively. The harder the car leans into a corner, the more the sway bar acts to "lift" the inside wheel—thus keeping the car flatter on extreme maneuvers.

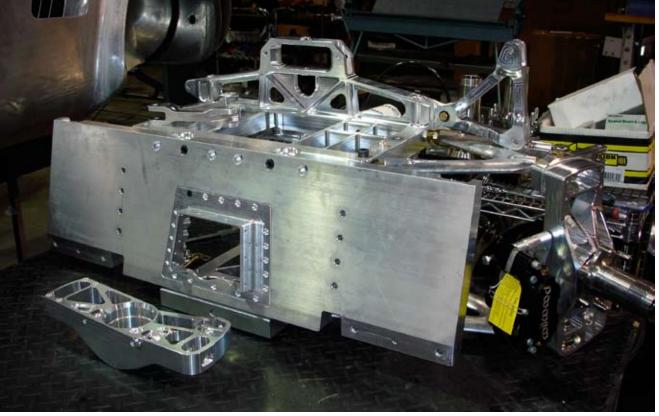




Front suspension box being assembled.



Rear suspension box being assembled.

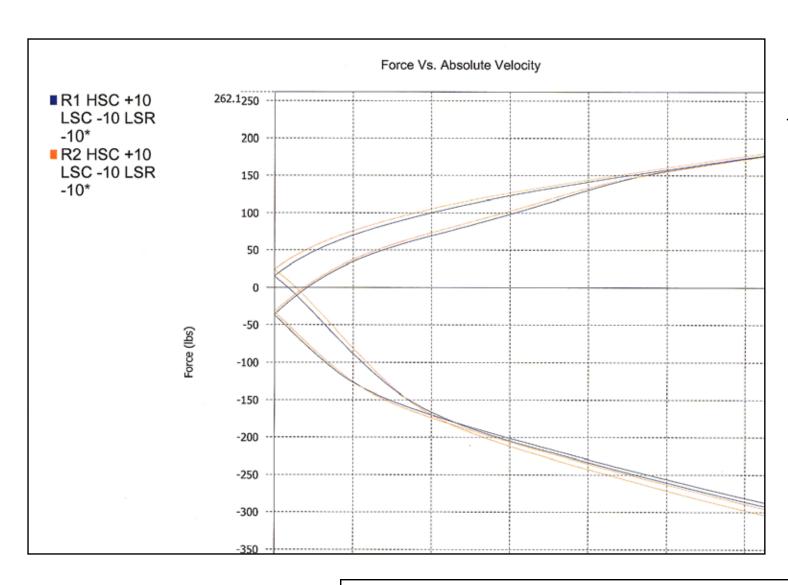




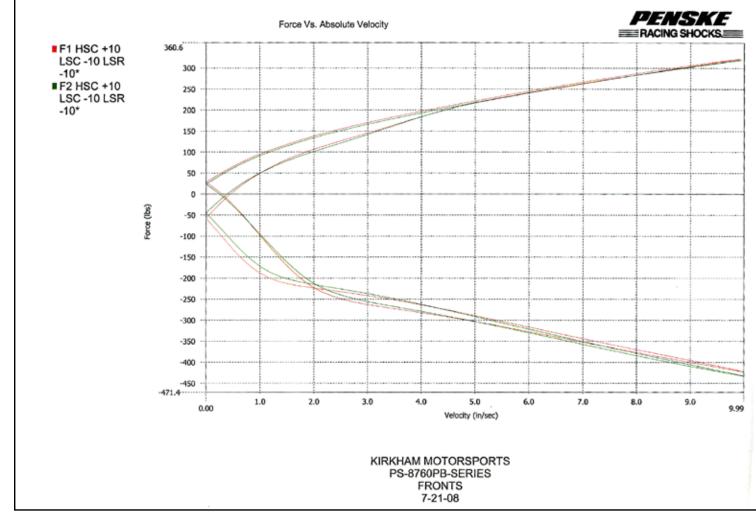
Rear suspension assembly.

The car's suspension was designed to be a push-rod system so we could accurately control the wheel to shock movement. The shocks are Penske triple adjustable—the best shocks money can buy. The shocks can be adjusted in fast jounce, slow jounce, and rebound. By decoupling the fast jounce from the slow jounce, we made the car more easily tuned for the street. The fast jounce is set quite softly—in case the driver hits a pot hole. We set the slow jounce quite firm. This slows down body roll as the car leans into a turn so the chassis isn't upset by quick, jerky movements. Also, from this angle, you can easily see

the "short arm, long-arm" design of the suspension. As the wheel moves up and down, the shorter upper control arm moves on a steeper arc than the longer, lower control arm. This "pulls" the top of the wheel in faster than the bottom of the wheel—camber gain. With proper camber gain, the tire stays as flat as possible on the ground as the car rolls in a corner. Our control arms are uncommonly long to minimize geometry changes as the wheel moves up and down. Longer arms move through their respective arcs slower than short arms—thus minimizing any upsetting effect wheel movement can have on the chassis.



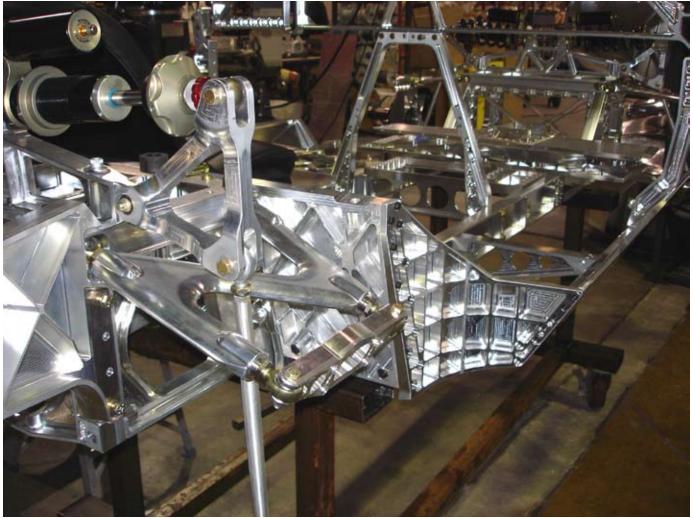
We used Penske triple-adjustable shocks for the car so we could finely tune the suspension.



These graphs depict the characteristics of the shocks as they were tested by Penske on their shock dyno.



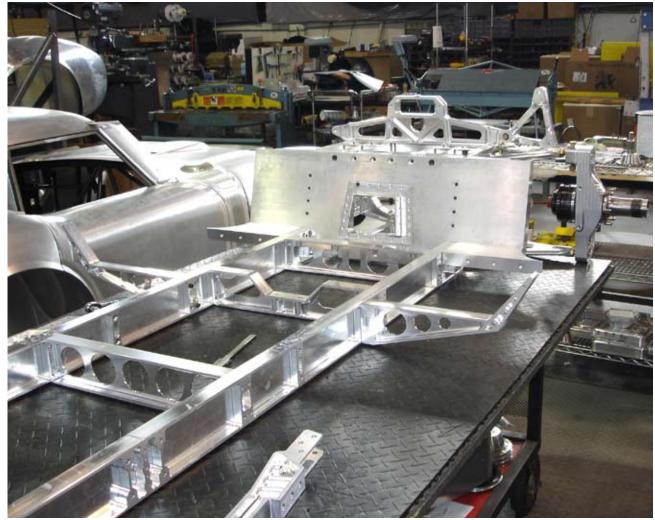
The front suspension box on the prototype car. The tunnel is sitting disassembled on top of the frame rails.



The right rear suspension coming together on the prototype car. This is an earlier version of the rear rocker.



Front suspension box assembled to the main frame rails.

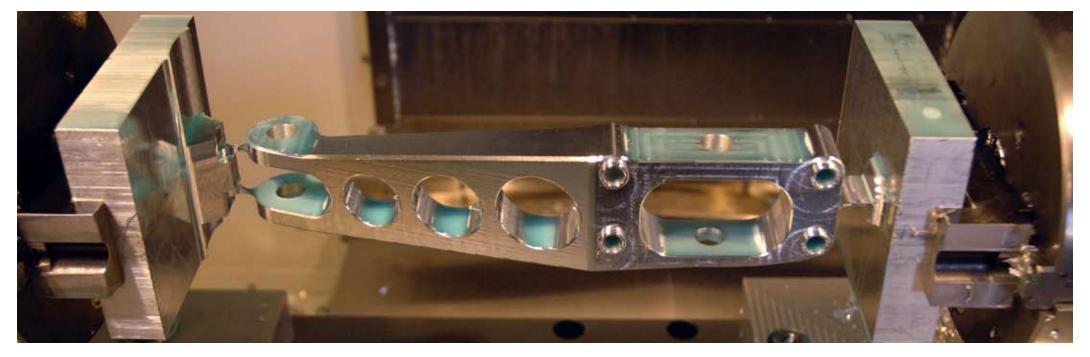


Rear suspension box assembled to the main frame rails.





Note the size of the original block. Most parts had over 90% of the aluminum removed during machining.

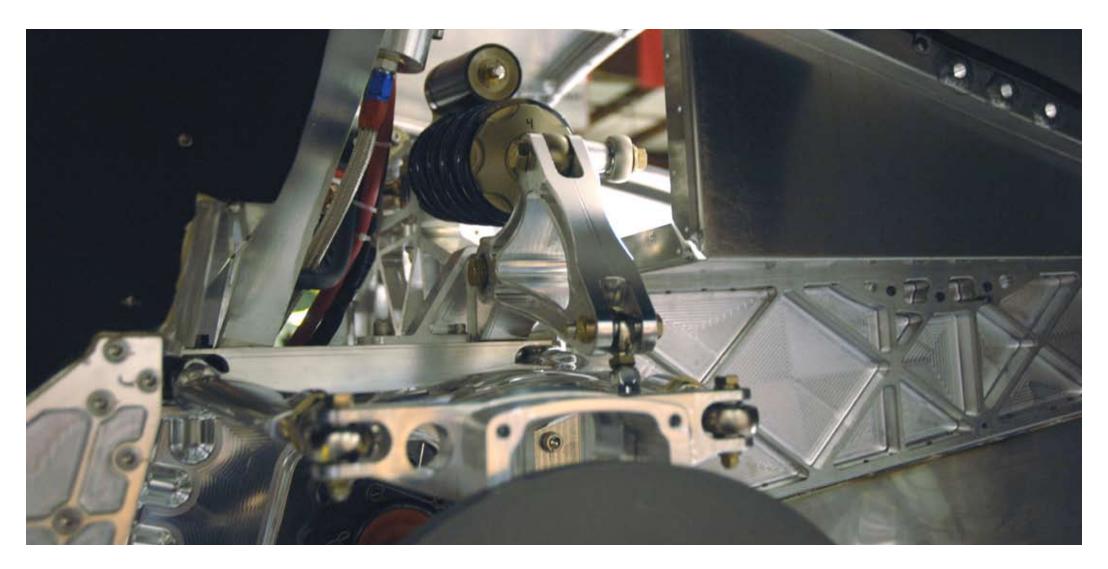




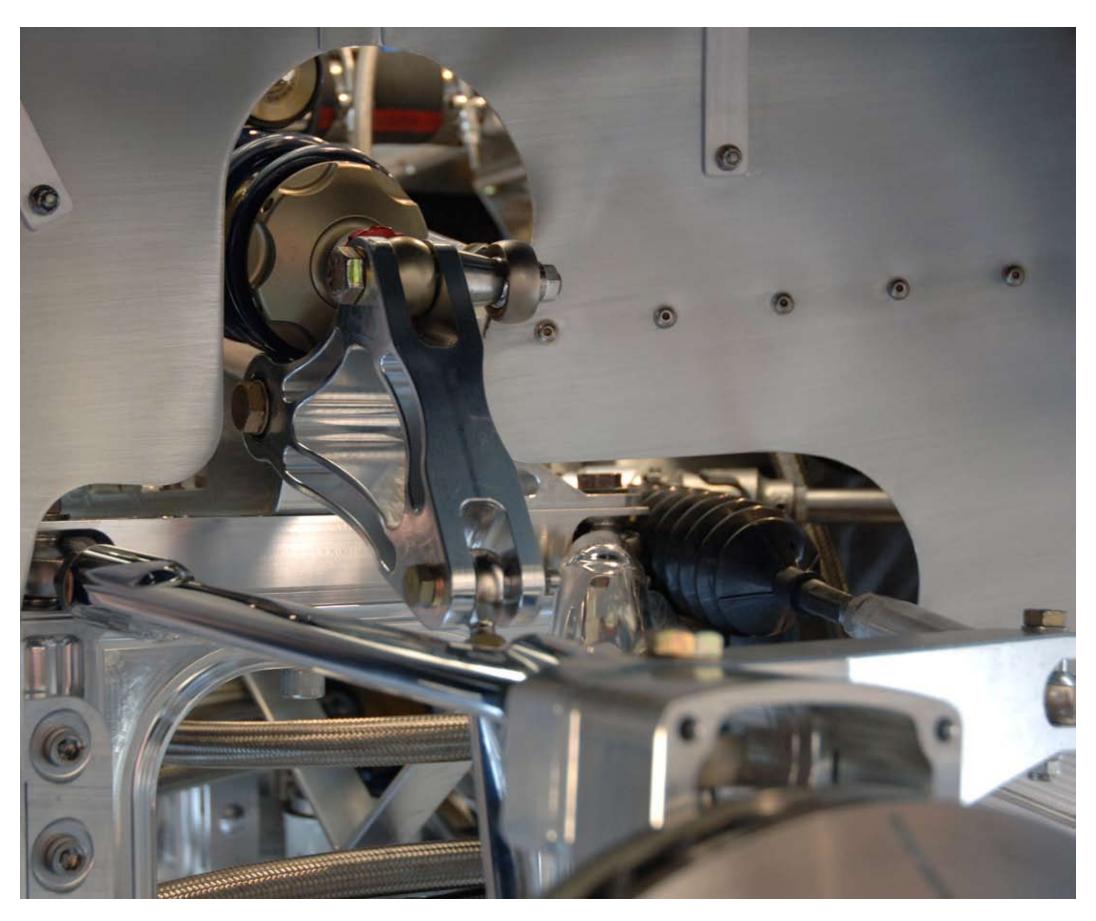
Front shock tower being machined from a solid plate of aluminum.

Closeup of a rear suspension rocker. If you look closely at the pivot bolt on the rocker, you can see the washer under the nut does not contact the aluminum rocker. The bolt clamps through the race of the bearing onto special hardened thrust washers that separate the rocker from the shock tower, thereby preventing the soft aluminum from being "point loaded" and ultimately failing due to creep.

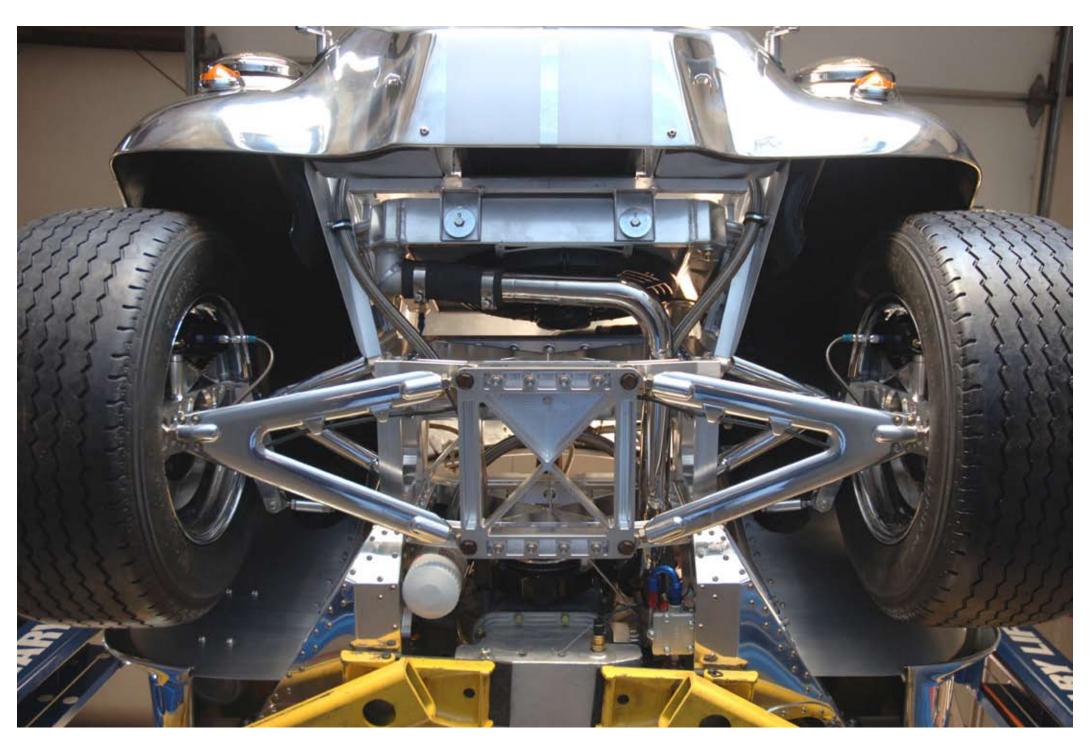




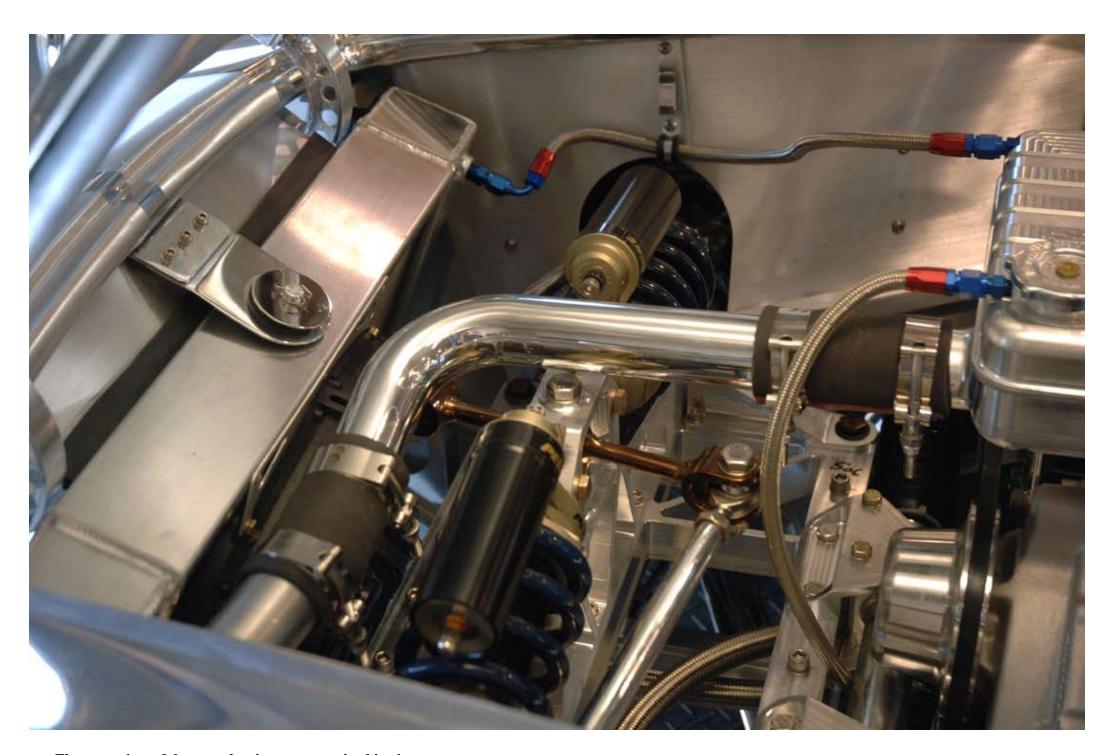
A closeup of the rear suspension rocker. Notice how the rod ends on the rocker and the upper control arm were designed to be mounted in double shear. Double shear minimizes bending loads on the parts.



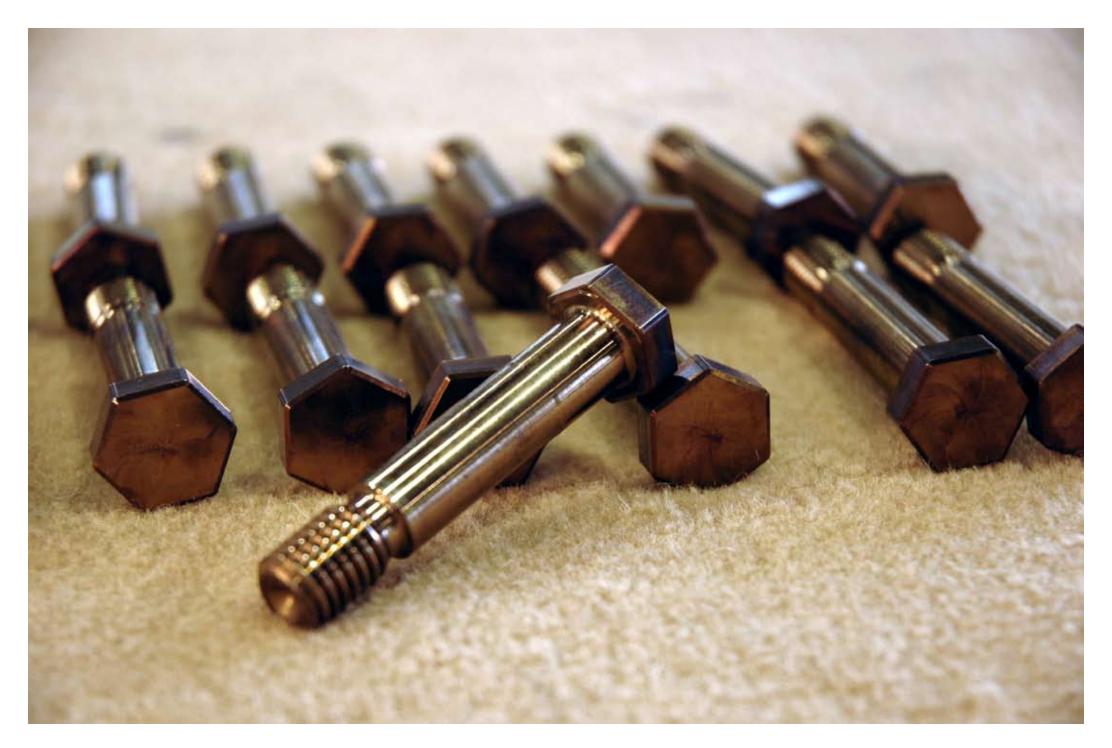
Finished front push rod and rocker assembly. The rocker pivots on roller bearings at all three points for an extremely smooth shock action. The rear rocker assembly is set up to pivot on roller bearings as well.



Finished front suspension. We mounted the oil filter low on the chassis to make changing the oil easy.



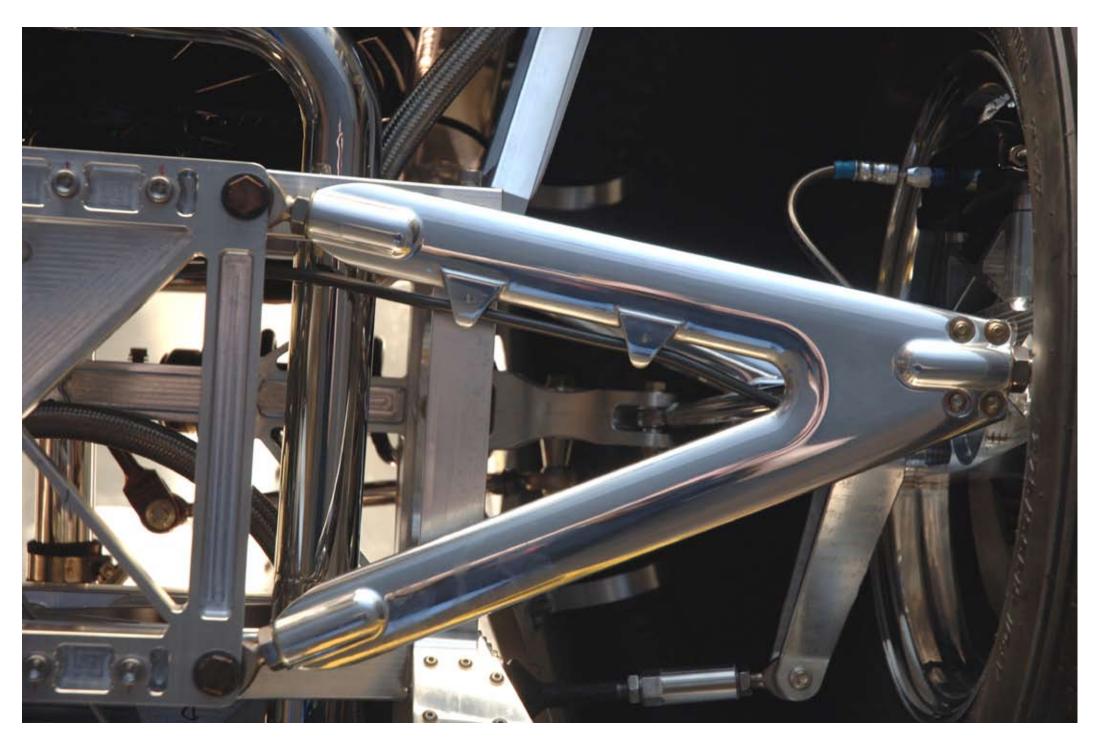
The operation of the sway bar is easy to see in this picture. The design of the sway bar is inherently progressive. The sway bar was machined from a 2-inch bar of 17-4 PH and then precipitation hardened in our shop.



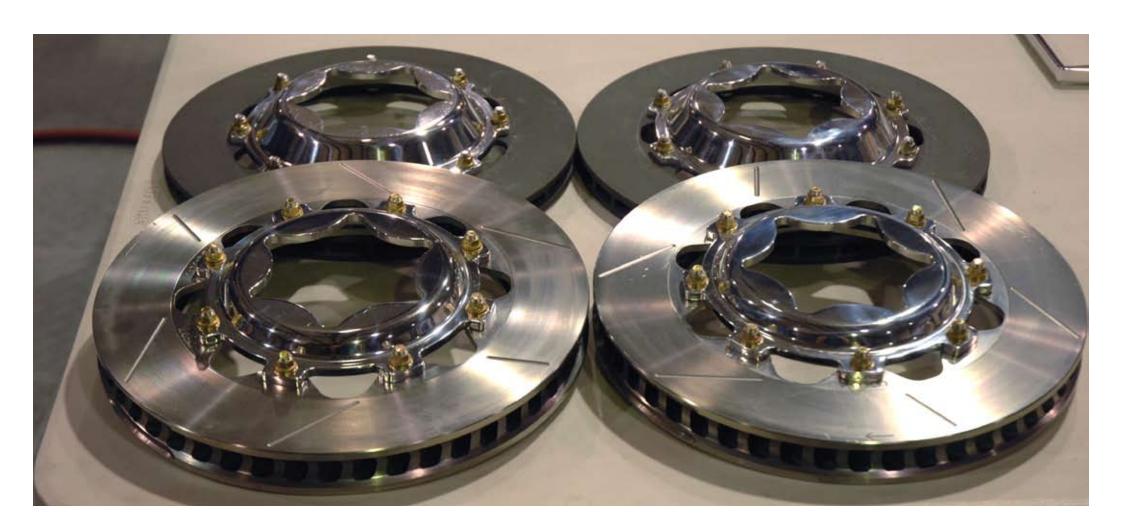
Custom control arm bolts made from 17-4 PH H900.

We custom made the suspension bolts. The greatest stress concentration on a bolt is at the root of the thread where it tapers out onto the shank. We relieved the end of the threads to remove that stress riser. The shank of the bolt is exactly 0.500 inches in diameter until it gets about 1/4 of an inch from the head of the bolt. There, if you look closely, you can see a faint line where the shank gets 0.005" larger in diameter.

The holes in the chassis must be slightly oversized (by 0.002") so the bolt can slip in. This minor slop in the hole, however, allows the shank of the bolt to rock in the hole on the chassis when the suspension is heavily loaded. This will slightly upset the alignment and kinematics of the suspension. To prevent this unwanted motion, the enlarged area on the shank "presses" itself into the chassis hole as it is screwed in, for a very tight fit.



The brake line brackets were machined directly into the control arm to save weight. We routed the brake lines behind the leading arm of the control arm to protect the lines from road debris. The long, sweeping curve of the control arm has a large radius to minimize stress where the arms blend together.



Brake hats and rotors.

The internal "tulip-shaped" ID of the rotor hats slips over the OD of the hubs. Little ridges machined into the hub prevent the rotor from falling behind the hub on the inboard side. On the outboard side the wheel keeps the rotor in place. The thickness of the rotor hat is 0.005 inches thinner than the space between the wheel and the ridge in the hub so the rotor can float axially (to leave room for thermal expansion of the rotor and hat). The rotor changes size as it heats and cools, but because the hat is driven by only the OD of the hub, it is completely free from the hub in all three axes-thus minimizing any brake shudder from being transmitted to the wheel. The rotor hats won't rattle but are safely clamped in place between the wheel and the ridges machined into the hub. Nevertheless, the rim never actually touches the rotor hat. Temperature changes in the rotor will not distort the hub—or transfer braking heat

to the wheel hubs. Distortion is one of many problems that lead to the dreaded brake shudder. One of the big challenges with race cars is keeping all the tolerances on the parts in the micron range to keep brake shudder away as parts are stacked on top of each other. Instead of stacking a bunch of parts on top of each other, we just eliminated most of the causes of brake shudder by simply decoupling the brake rotor hat completely from the hub and wheel assembly. I have never seen anyone else do it this way-probably because this procedure requires a lot of very tight tolerance machining. We did, however, use the Ducati brake system as inspiration (more standing on the shoulders of giants to see a little bit farther). The rotor hats were completely polished to remove any stress risers from the machining process. The slots in the rotors wipe the boundary layer of gas and dust off the pads for enhanced braking.



Wilwood 6 piston, differential bore calipers

The front calipers are 6-piston Wilwood units. The leading bore of the caliper is smaller than the trailing bore to give a slightly higher clamping force on the trailing piston.

As the rotor sweeps through the caliper, the trailing edge

of the pad is hotter and so the coefficient of friction is slightly lower—hence the trailing piston needs to clamp with a slightly higher force to keep the pad square to the rotor under extreme braking conditions.



Polished rear upper control arm.





We designed our own aluminum E-brake calipers to be as lightweight and compact as possible. We used a 12.2" OD rotor in a 15-inch rim, leaving very little space to work with.



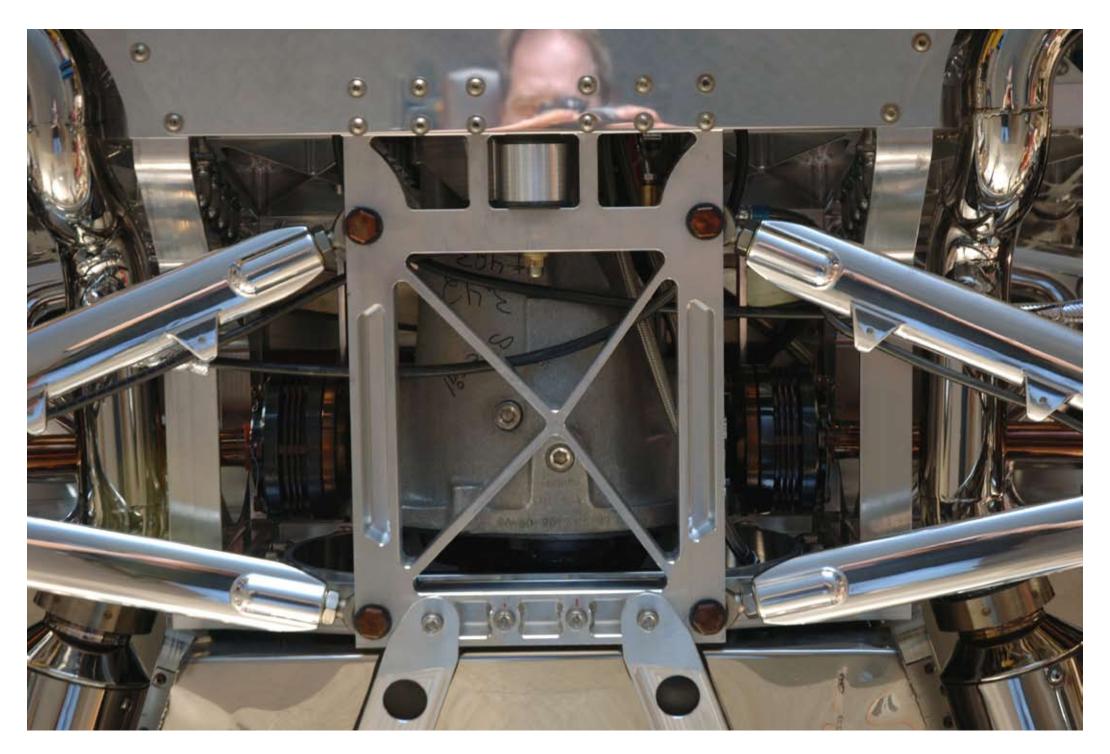
We mounted the push-rod as far out board on the front lower control arm as possible to minimize any bending loads. Also, notice the upper and lower ball joints are held in double shear for maximum strength.



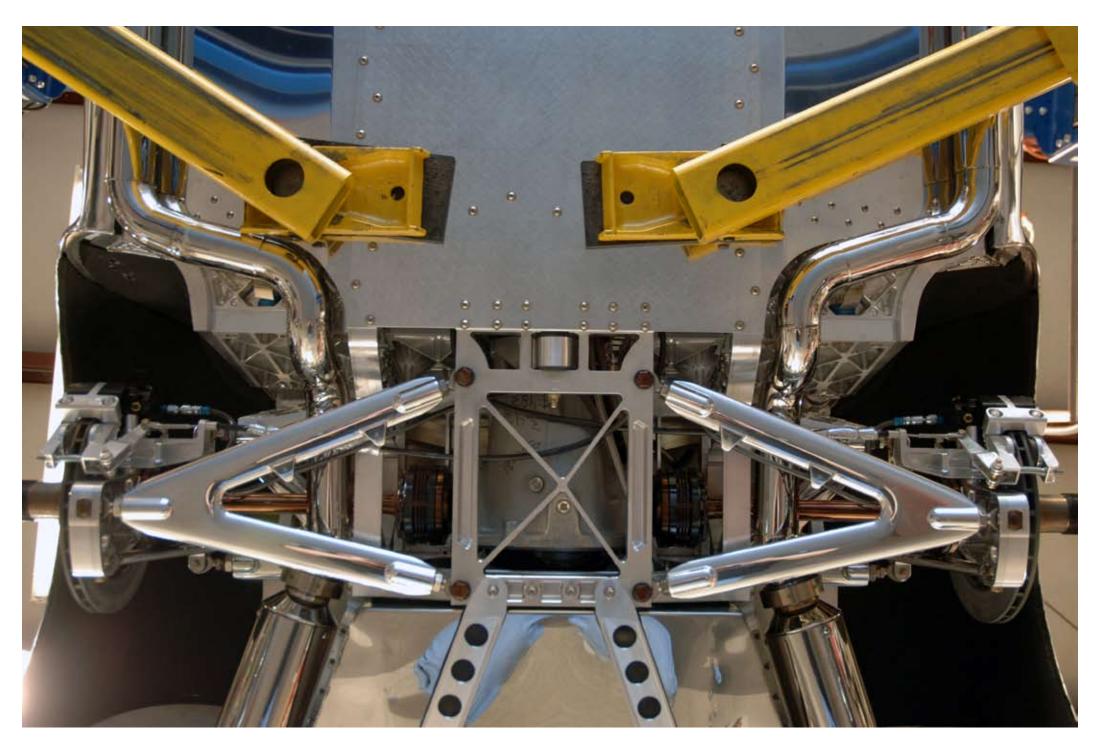
Nickel plated 4340 chromoly rod ends.

We designed the ends of the rear upper control arms with an ingenious adjustment system we saw on Lemans GTP cars. The rod end has a 1/2 inch left-hand thread that screws into the bronze colored adjustment sleeve we made. The bronze-colored sleeve (made from hardened 17-4 PH) has 1/2 inch left-hand threads on its inside diameter and a 3/4 right-hand thread on its outside diameter. The larger threads on the OD have a large surface area to help prevent the threads on the aluminum control arms from creeping under prolonged loading. Because of the opposing left-hand and righthand threaded setup of the adjuster sleeve, simply turning the sleeve provides for infinite adjustment of the length of the control arm. When all adjustments are finalized, simply tightening the jam nuts on both the top and bottom of the sleeve locks it in place.

In this close-up view, you can see the high-quality rod ends we used throughout the car. The rod ends are made from heat-treated 4340 (a nickel-molybdenum based chromoly) for superior strength and fatigue resistance. Polishing the rod ends to remove all stress risers further improved the fatigue life of these highly stressed parts. Finally, the rod ends were electroless nickel plated to eliminate the possibility of hydrogen embrittlement from standard plating practices. If you look closely, you can see the Teflon lined outer race (a thin brown line between the inner and outer races of the rod end). All rod ends we used in the car were Teflon lined, so no grease is necessary to lube them. Grease attracts dust and grime and prematurely wears rod ends out. As a final touch, the jam nuts are made from stainless steel to prevent corrosion.



Looking straight up at the differential on the finished car. Notice all the stainless steel bolts. Here you can see the inboard side of the 1/2 shafts. The differential is marked with a 3.42 in magic marker—indicating it has a 3.42:1 gear ratio.



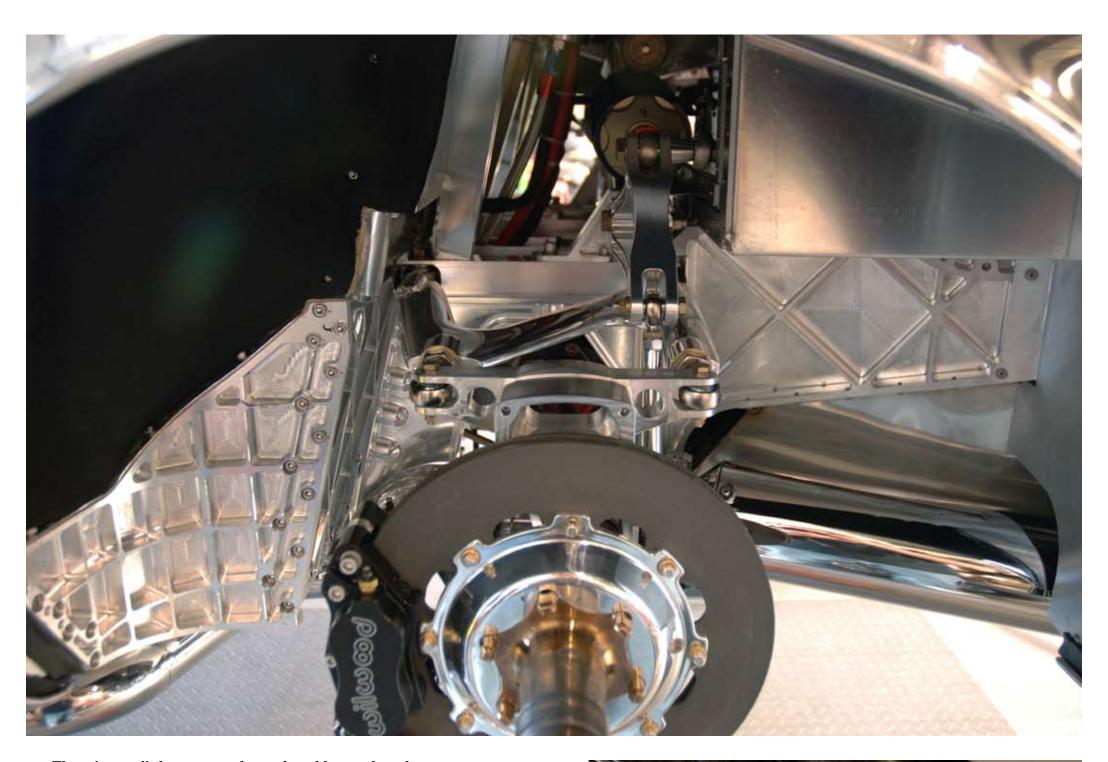
This shot is zoomed out a bit so you can see how everything was very carefully packaged together to fit in an extremely small area.



Billet aluminum knock off.

The hub knock offs were machined from a solid billet of aluminum. Following years of racing tradition on all high-performance race cars, the hubs on the left side of the car are machined with right-hand threads, and the hubs on the right side of the car are machined with left-

hand threads. If you look closely at the center of the wing nut, you can see "OFF" with an arrow engraved in the clockwise direction. This indicates this knock off is for the right side of the car. We machined the knock offs with a thicker base so they don't bend as easily as the originals.



There is very little room, so the push-rod has to thread between the arms of the rear upper control arm. You can also easily see how the rod ends on the rear upper control arm are captured in double shear. Camber and toe adjustments are done on the upper control arm with sleeve nuts.

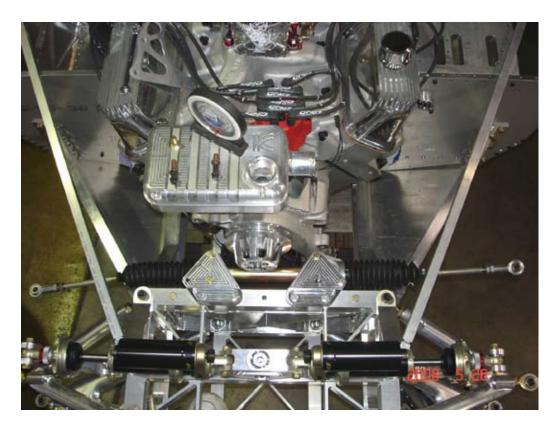
All the control arms were designed with maximum radii to minimize any stress risers in the parts. Additionally, the control arms were polished to a mirror finish to absolutely minimize any stress risers. Here you can also see the brake flex line brackets that were machined directly into the control arms.



## STEERING RACK

Do, or do not. There is no try.

Yoda, George Lucas





We purchased a steering rack from a highly regarded manufacturer. Then, when we tried to align the car, the measurements randomly kept moving all over the place. With the help of a laser, we finally isolated the problem to loose bushings in the housing. When we took the steering rack apart, we noticed the rack bushings were kept in place only by a triangular

swage on the housing—which, in turn, squishes the bushings into a very sloppy, triangular shape! When I told the manufacturer the end play in his rack was 0.060 inches, he said, "What'd you expect—an Indy rack?" The only way to fix this problem was to cut the steering rack apart on the band saw and make our own tube and bushings.





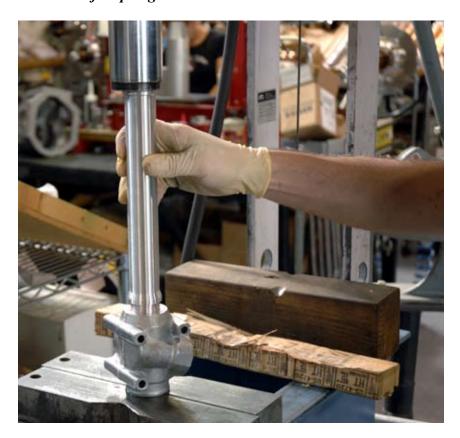


Milling the remaining part of the tube out of the housing.

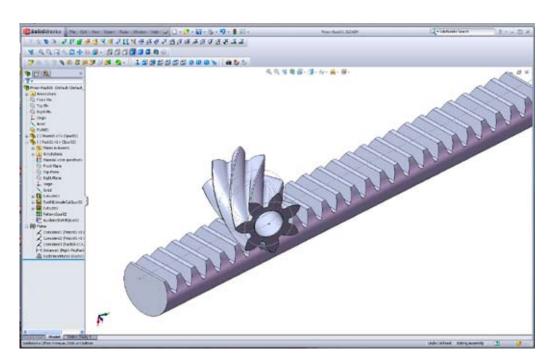


Warming up the housing to get it to expand.

We made a new steering tube and pressed it into the housing (below). We cut a special snap ring (right) out of titanium on the water jet to hold the bushing in place. Titanium is a wonderful spring material—and it doesn't rust.

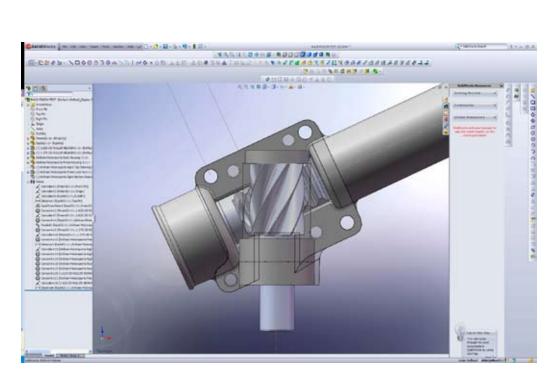




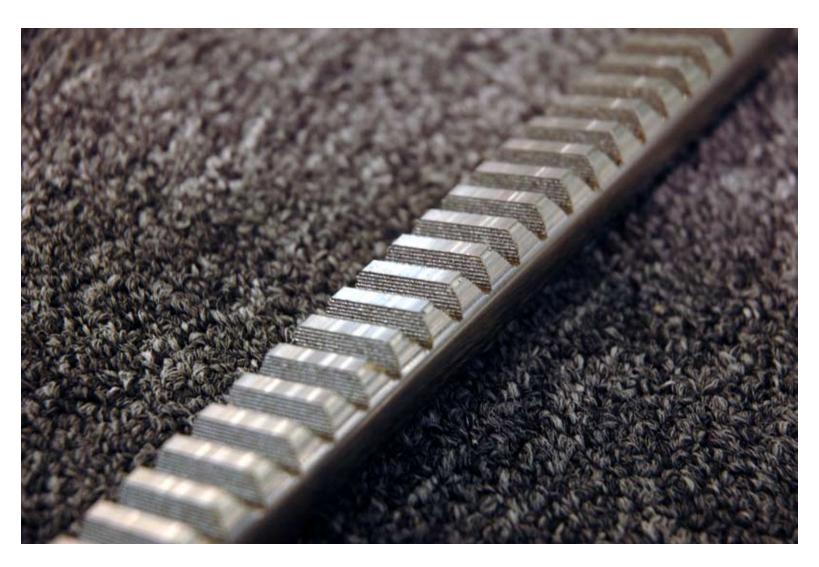


After all that work, we put the problem rack back in the car and found there was a shimmy in the steering wheel when driving. We traced the problem to the pinion bearing. Unbelievably, the manufacturer cantilevered the pinion in the rack housing on a sloppy bearing that couldn't take thrust loads. As the driver turned the steering wheel, the pinion rode up or down the rack before the slop ran out of the bearing and the rack started to move—translating to the vibration in the steering wheel. So, the "non-Indy" steering rack went into the trash and we went to the drawing board and designed our own steering rack from scratch.

Notice there are always three faces of the pinion gear in contact with the rack at all times to minimize backlash. Making our own rack worked out better in the end anyway. We were able to design the pinion angle, travel/revolution, and package size exactly how we wanted it.



We custom made the pinion at 25 degrees to clear the water pump on the engine.



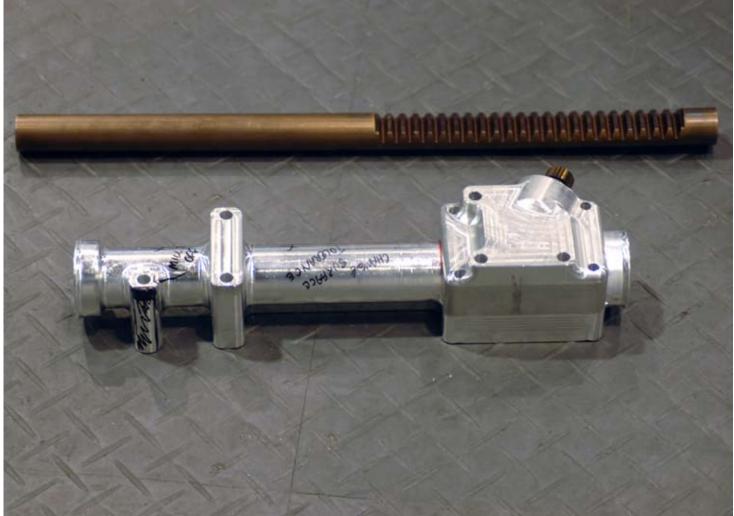
Making the rack turned out to be quite challenging. When we machined the first rack for the prototype, the rack stress relieved and bent into a banana. We were able to straighten it almost perfectly...but we wanted Larry's rack to be perfect. So when we machined his rack, we rough machined it and then straightened it.



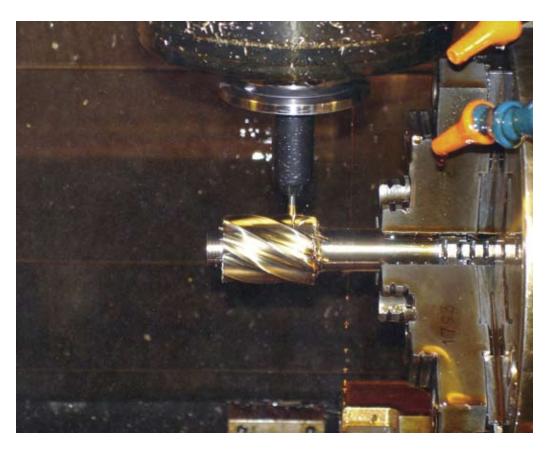
After we straightened the rack we did a finish pass of the final 0.010 inches.



Instead of making the rack out of three different pieces (like everyone else), we cut the rack housing from a single block of aluminum. That way we were guaranteed to have a perfectly straight rack housing.



The bronze color of the rack indicates it has been heat treated. The rack housing is now completed for the prototype car as well. Notice the writing on the rack and the colored-in areas. Those areas were modified for the delivered car.



The pinion is machined on our 4-axis mill with a tiny 1/16 inch ball mill. We then profile the gear pattern.



The pinion had to be extremely short so it would not hit the engine.



We machined the rack and pinion from Maraging 300. Maraging 300, like its name, has an ultimate tensile strength of 300,000 psi. All stainless materials are NOT the same! When Maraging 300 is hardened, it achieves a Rockwell hardness of about 52 RC—perfect for gears. Because the material is precipitation hardened—not quench hardened—we didn't have to worry about micro cracking. Maraging 300 is used to make the gears in F1 race cars. Interestingly, it is one of the only materials that can be used to make uranium centrifuges. Notice the boss on the back of the gear for a bearing—we supported the pinion on both sides to prevent any cantilever motion as the pinion was heavily loaded.



We mounted the steering rack in double shear to prevent it from flexing under extreme driving. Here are the top and bottom steering rack plates coming out of the machine.

We used Vespel for the bushing material. Vespel is an extraordinary plastic that is made by DuPont. It has almost unbelievable properties. It can flash to 900F degrees and has a working temperature of 550F degrees. Here you can see the Vespel bushings were machined in place so they would be perfectly in line with the rack.





Vespel has the lowest coefficient of "stiction" known, so the rack moves incredibly smoothly. As you might guess, this is the material used in F1 steering racks, satellites, and space shuttles. Only a few inches of the raw material for the bushings was over \$500.



We designed the steering rack with a nut that fit around the pinion so we could clamp the pinion bearing securely in place. This design enabled absolutely no relative movement in the pinion.



The underside of the pinion housing.



Left: Notice the machined Vespel in the housing as well as the machined hole in the far left of the housing. The hole creates another anchor point to support the rack as far out as possible.

Below: Final assembly of the rack. We used Mobile 1 synthetic grease for the gears. Also, if you look closely, you can see the rack is not bronze colored any more. After heat treat, we polished the rack to a mirror finish so it would slide as smoothly as possible.





The final installed steering rack. It just barely clears the water pump. You can see the water pump pulley actually sits over the top of the rack. The steering shafts are all made of stainless steel in the entire steering system. The steering U-joints are stainless steel as well. We wanted this car to resist the ravages of time for as long as possible.

## **ENGINE AND TRANSMISSION**

Yield to temptation. It may not pass your way again.

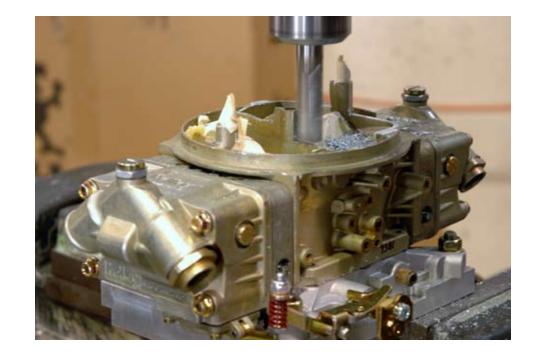
Robert Heinlein



The heart of this billet Chariot of Fire is an asphalteating aluminum FE 427. The engine has 4340 H-beam connecting rods and a 4.25 inch stroke x 4.25 inch bore for a total of 482 cubic inches. The aluminum block was made by Shelby. The aluminum heads are made by Edelbrock. Keith Craft built the engine and

did his magic 5 axis porting on the heads for incredible flow. We specified a hydraulic roller cam in the engine to minimize maintenance. The engine dyno'd at 643.5 horsepower at 6300 rpms. Torque is 600 foot pounds at 3000 rpms. This gives Larry's car a power-to-weight ratio greater than a Bugatti Veyron.





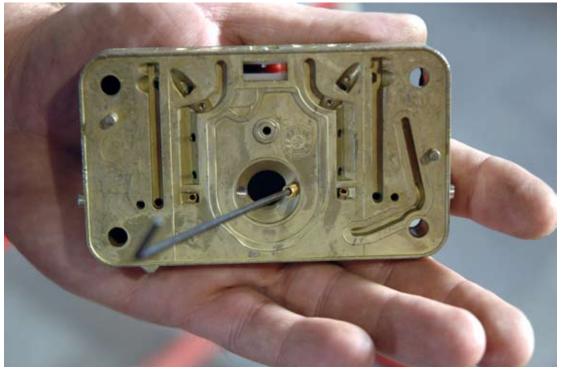
Milling off the factory air horn for greater air flow.

There were many modifications we did to the carburetor to make the car more streetable. We started with a standard 830 Holley double pumper carburetor. We use the 830 because it has large annular boosters that can react faster to the slight throttle differences encountered in street driving. By drilling and tapping the bleeds in the metering plates, we can precisely control the fuelto-air ratio between idle, transient response, and full throttle.

The factory fuel bleeds are too rich for the motor.

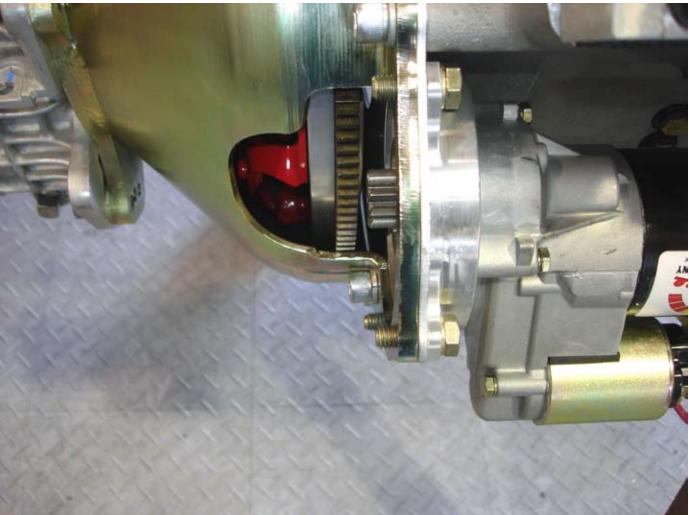


By drilling a very small hole in a set screw and tapping fuel bleeds, we control fuel flow precisely.





The engine prior to installation It is always easiest to set up everything on the engine while it is out of the car. The alternator, however, is in the way.



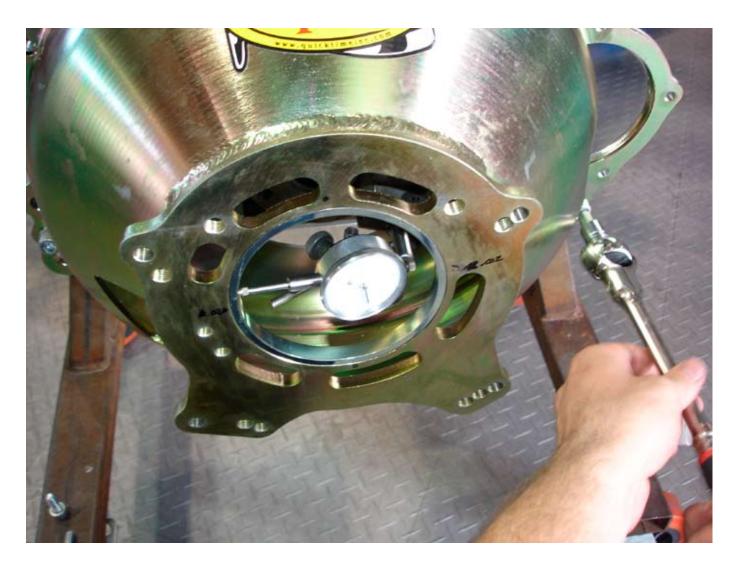
One thing almost everyone forgets is to measure is the distance between the flywheel teeth and the bendix gear on the starter. If the starter is too far away, it will not completely engage, and it will chew the teeth off of the ring gear. If it is too close, it will not release.



With this setup, fuel flows past the carburetor and into a bypassing fuel regulator. If the fuel pressure is too high for the carburetor, the regulator sends the extra fuel back to the tank. A bypassing fuel regulator is the best way to keep the carburetor's fuel cool, as fuel is always circulating. If the fuel sits too long in the fuel line the engine heats it up causing vapor lock. The fuel pressure reading is also taken after the carburetor for a correct reading.



We made a special radiator expansion tank with the outlet facing forward so the radiator tube would clear the shock.



The bell housing must be aligned within 0.012 inches of runout. If the transmission is not in line with the crank shaft, there will be a bind on the input shaft causing the transmission to shift poorly.



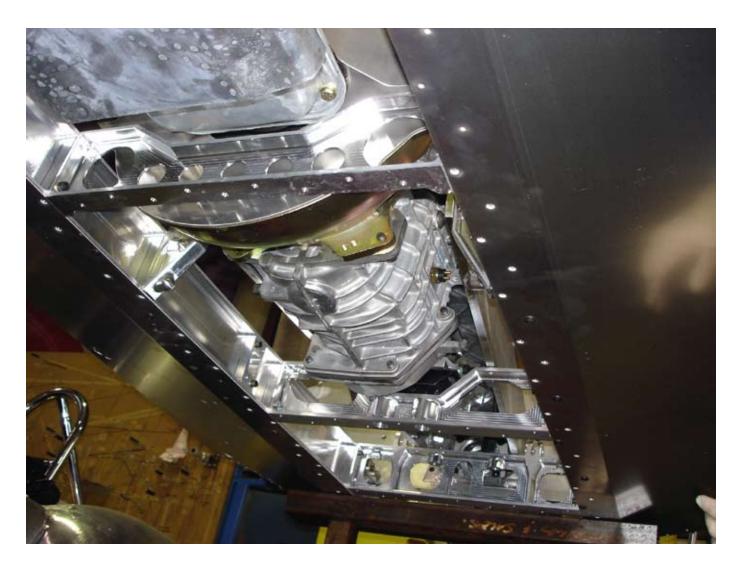
Because there was simply no room for our normal throw-out bearing assembly, we opted to go with a Tilton unit like that used on all modern race cars. Once the motor was installed, however, the clutch pedal felt like a bear trap—it had to go. The prototype car still has this throwout bearing setup.



I could not stand the high pressure of the throw-out bearing so we had to find another answer. As there was no room in the standard location for the throwout bearing arm, we moved it to the top of the bell housing. Here I am welding a special bracket we cut out on the water jet onto the bell housing to hold the slave cylinder.



The slave cylinder pushes on the clutch arm with a rod end. The billet clutch arm also pivots on a rod end. This makes for a very smooth clutch action. There are two holes on the clutch arm—the upper hole is for an easier, but longer, clutch action. The lower hole releases the clutch faster—albeit at a higher clutch force.



Prototype: We used the construction of an airplane as inspiration for the design of the chassis. The main frame rails form the longerons and the belly pan are a stressed skin. By moving the stress to the outer skins, we were able to make the chassis very stiff.



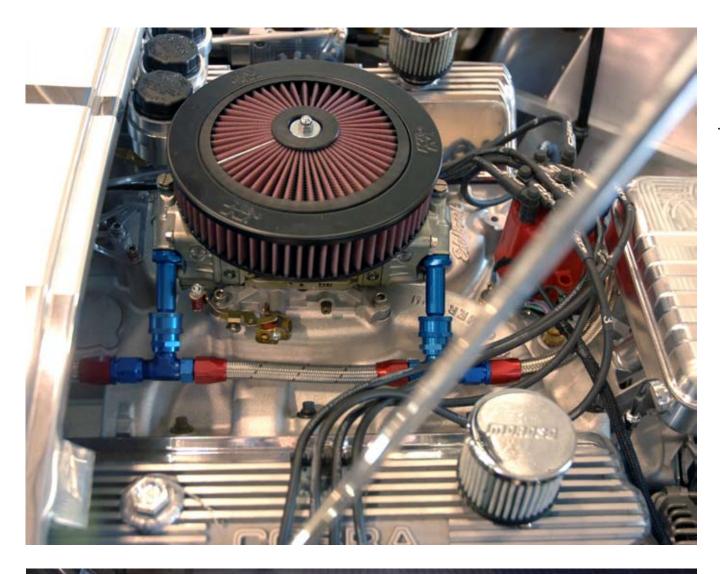
There was very little room to make everything fit. The battery cables are 1 gauge fine-stranded welding cable to carry the current all the way to the engine—even if things warm up under spirited driving.





Far left: When the motor was installed, we noticed the shifter mechanism was quite bulky and would have looked ugly in the car. So we removed the shifter box and machined our own (left) that was much smaller. Below, the new shifter box is installed.

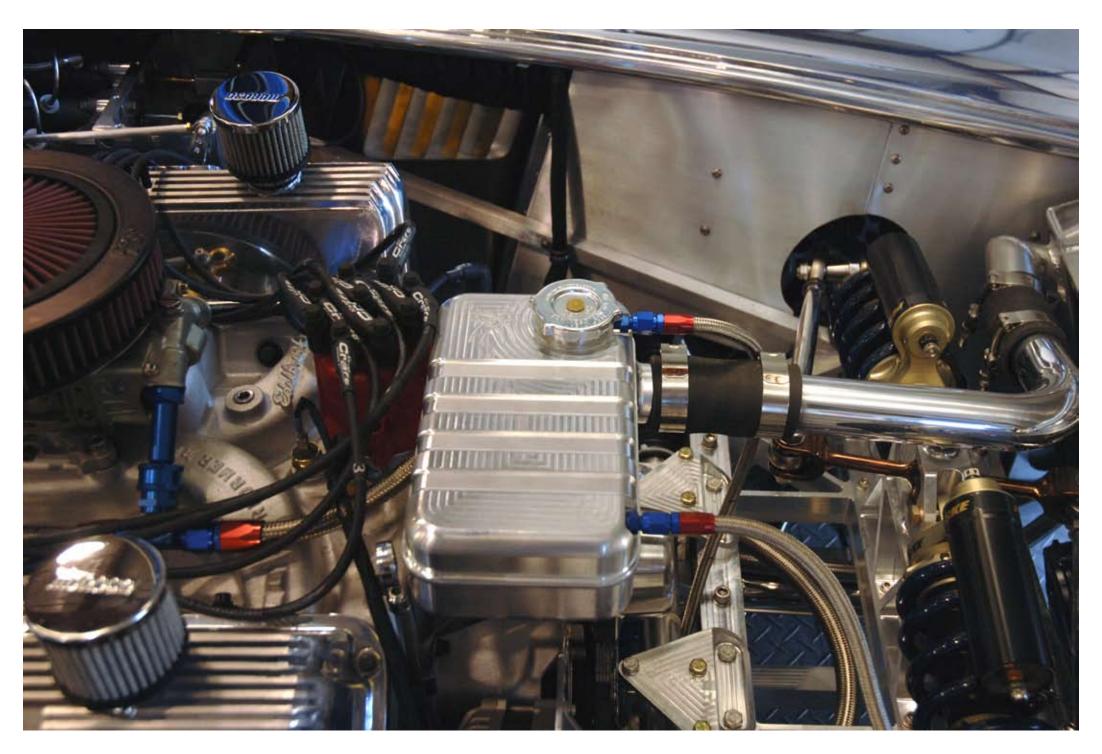




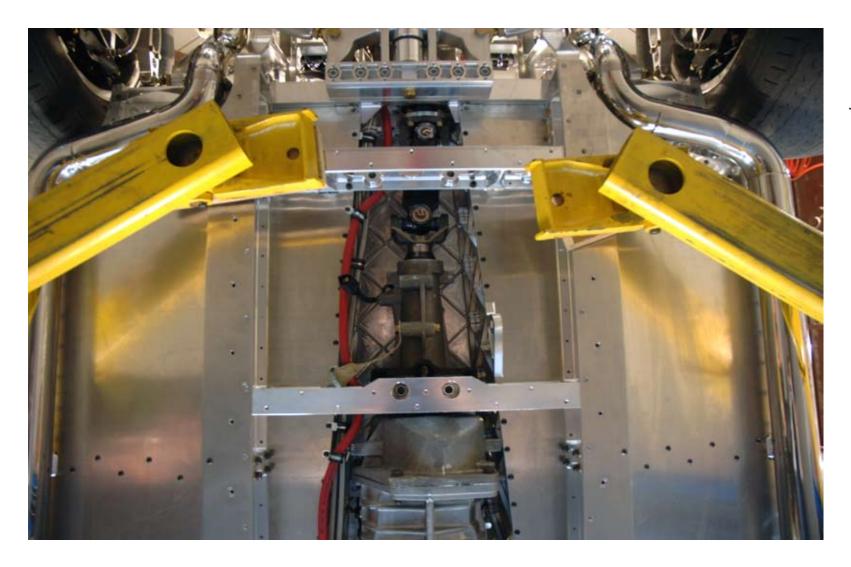
Here is the final engine placement in Larry's car as it was delivered to him. Notice the distance from the back of the air cleaner to the edge of the hood jam is only about 2 inches.



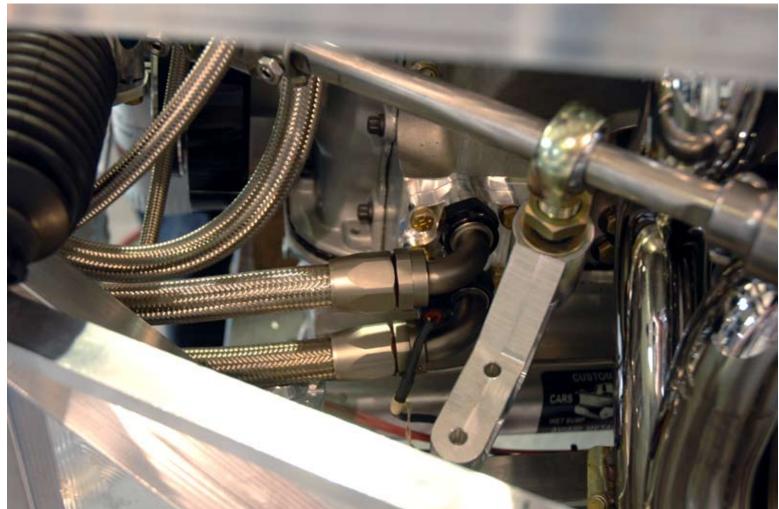
This is a picture of one of our standard cars with the engine installed. Compare with the billet car photo (above). We moved the engine back 6 inches for enhanced weight distribution.



The outlet for the radiator tank had to face forward so the coolant could pass between the shocks. In this picture, you can also see the car sitting on the ground at ride height because the angle between the sway bar and the sway bar links is 90 degrees. The sway bar is "softest" when it is positioned at 90 degrees.



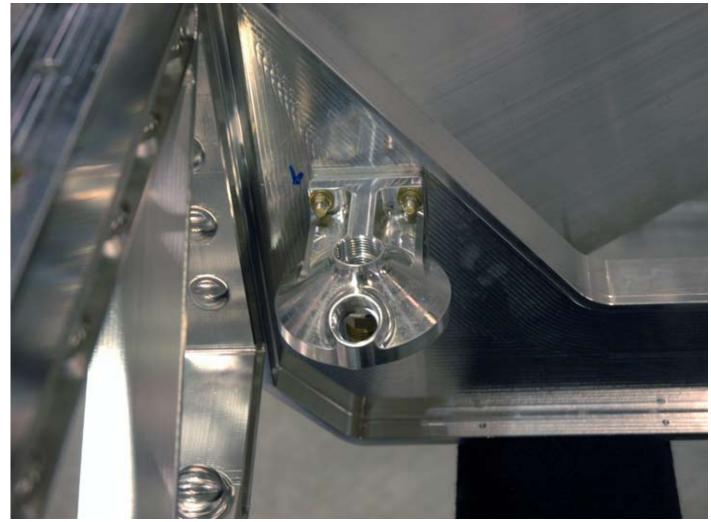
The tunnel is being trial fit for final assembly.



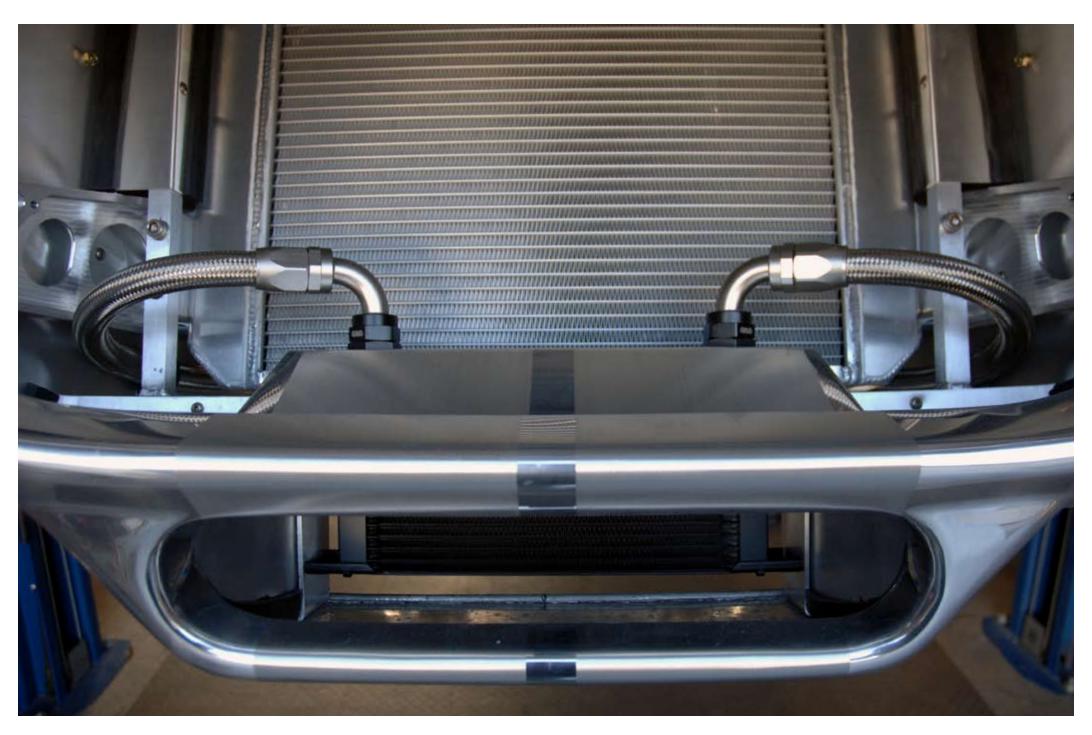
The oil cooler lines have special "double swivel" fittings on the ends. The hose is free to swivel on the fitting, and the fitting is free to swivel on the motor. Many failures occur because the hose is rigidly mounted and it fatigues and cracks from the engine vibrations.



Here you can see a specially threaded fitting we machined and welded in where the original valve cover breather used to be. Notice the safety wire to prevent the plug from vibrating out. We discovered we had to move the breather to the front of the valve cover when Desire Wilson, a retired F1 pilot, took the prototype car out for some hot laps. We watched her lap faster and faster as she gained confidence with the chassis. When she finally returned to the pits, she had filled the passenger footbox up with engine oil. Because of the extreme cornering and acceleration G-forces the car was capable of, oil was trapped in the back of the valve cover and ran out past the breather. At least Desire was smiling.



We mounted the oil filter lower in the chassis to make changing the oil easier—and cleaner. This is a picture of the oil filter bracket. These fittings are also of the double-swivel type.

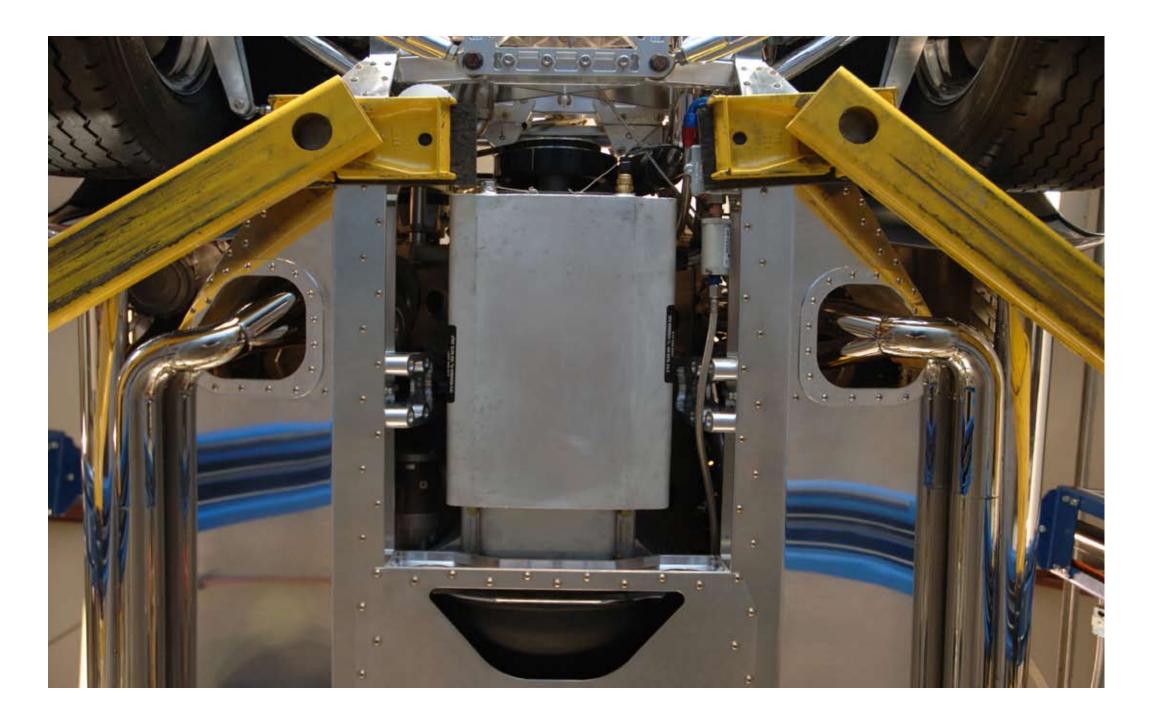


The oil cooler also has double-swivel fittings. These special fittings eliminated an extra adapter on the end of each fitting—another potential source for leaks. On this car, we continued the brushed stripes right onto the oil cooler shrouding.

## **EXHAUST**

Imagination rules the world.

Napoleon Bonaparte

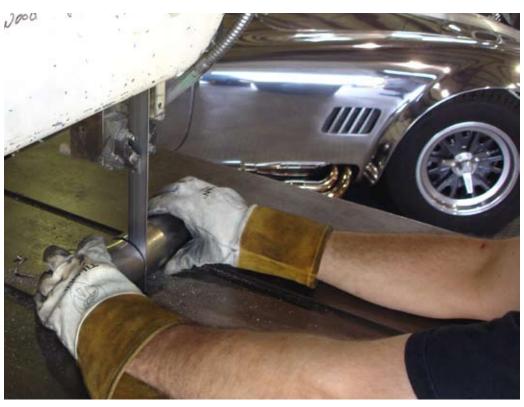


The under-car exhaust was a huge challenge. Original side pipes are relatively easy, as all you need to do is cut holes in the body and run the pipes out. An under-car exhaust, however, has to be carefully planned out so the exhaust doesn't negatively affect

the already low ground clearance of the vehicle. After dropping out of the engine compartment, the pipes immediately turn to the sides to run under the rockers. The area around the oil pan and bell housing was cut out to allow heat to leave the engine compartment.



Our CNC tube bender will make extremely tight 1D (one diameter) bends. We needed tight bends to make the exhaust.



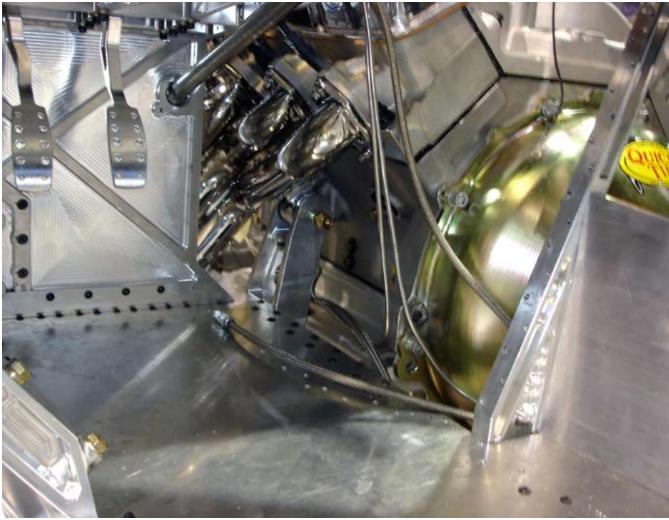
We bent up several "U" bends—and then began the tedious cutting and piecing of the exhaust system.



Here you can see some of the cut-up tubes as we were building the exhaust. The mufflers are 100% stainless steel. Even the packing is stainless steel wool—it won't blow out like fiberglass does. We polished the mufflers before assembling the exhaust system.



Moving the engine so far back posed large problems for the exhaust system design. The rear two exhaust ports had to have their exhaust pipes come forward before they could merge and make the turn back.



On the prototype chassis you can see the rear two exhaust ports are right above the driver's leg. Heat control was a very high priority. Here you can see the pipes running forward—before they merge.



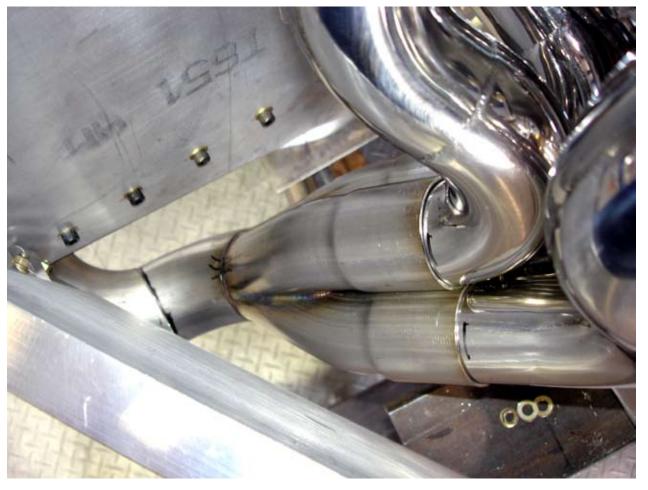
Notice how the merge collectors smoothly merge all four exhaust tubes (per side) into a single flow. We polished the merge collector separately because it is much easier as a separate piece. The purpose of the merge collector is to speed up the flow of the exhaust. Because the four merge into a smaller area, the exhaust must speed up—having a scavenging effect on the cylinder heads, which produces more power.



There was very little room for the merge collector We tried three different lengths of collectors before we got all components to fit perfectly.



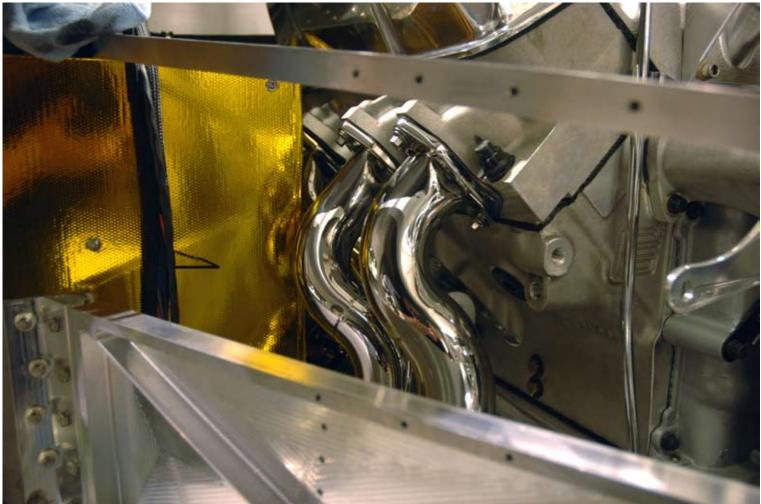
Here is a look inside the exit side of the merge collector. Notice the nice, smooth pyramid in the center of the four tubes. All burrs were sanded smooth for unobstructed exhaust flow.



After we pieced the tubes together, we mounted each side on a head. Here we did the fine tuning to make sure all the tubes came together absolutely evenly so the merge collector could easily slide on and off.



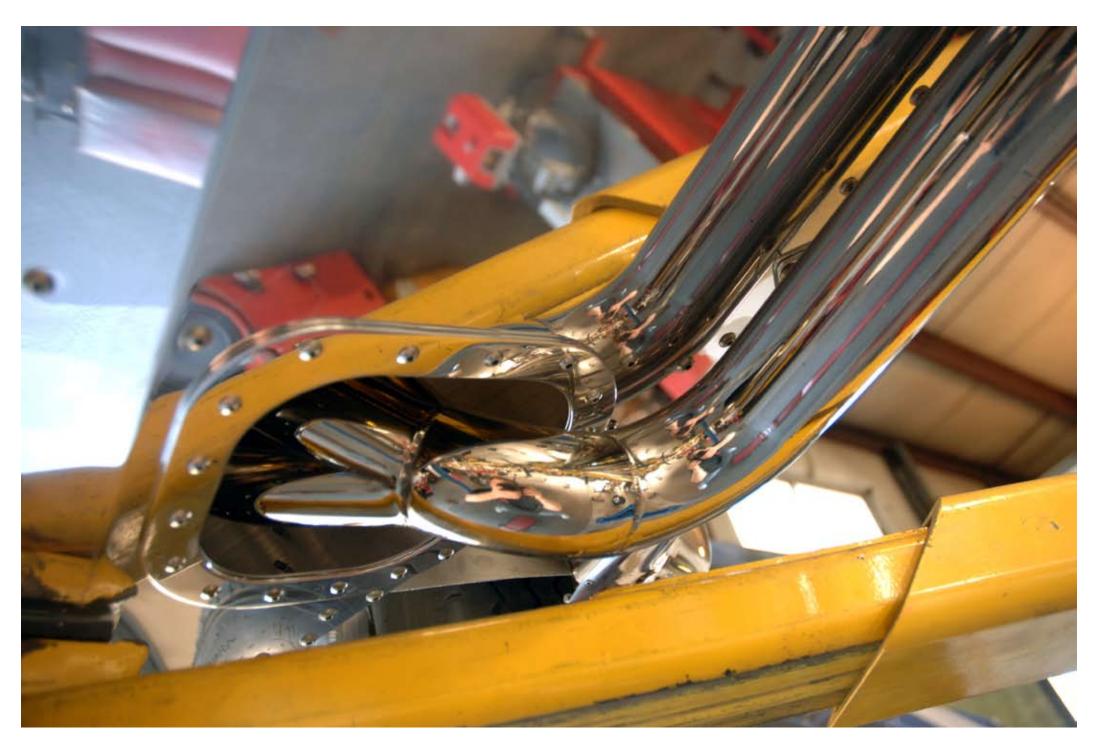
We used three layers of heat protection for the driver: Kevlar backed gold foil, stainless steel heat shield, and Aerogel aerospace insulation.



Passenger side exhaust tubes 1 and 2.



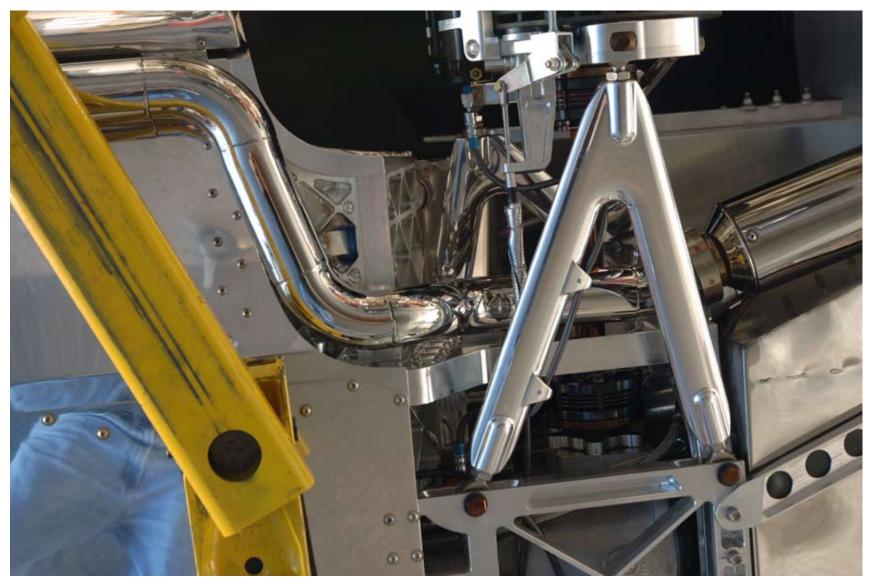
When the exhaust exited the engine compartment, it had to immediately bend out—and up—to the side of the car. There is more clearance on the edges of the belly pans. We made a special doubling plate to strengthen the exhaust cut out in the belly pan so it would not fatigue and crack.



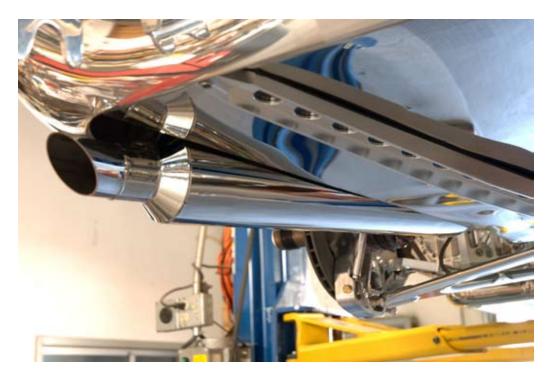
The underside of the car where the exhaust swings back up to tuck tightly against the belly pan.



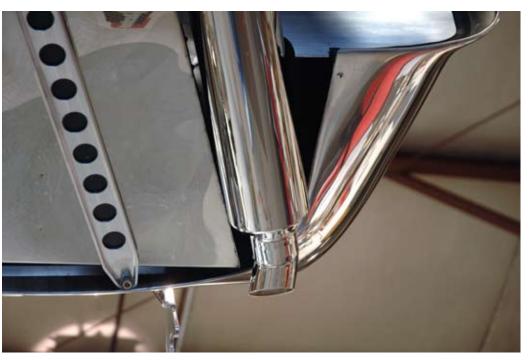
There are 5 different sections in this photo where the exhaust makes a turn to thread through the rear suspension.



The exhaust went over the rear lower control arm and under the 1/2 shaft. We did this to maximize road clearance for the exhaust.



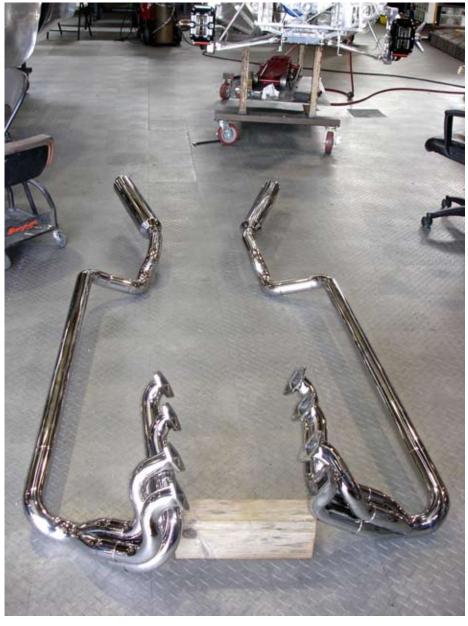
Rear exit exhaust.



We ran the muffler as close to the gas tank as possible for minimum disruption to under-car air flow.



Once everything was fit, we polished the exhaust to a mirror finish. The finished exhaust was very light, compact—and beautiful.



## COMPONENTS

It is not the mountain we conquer but ourselves.

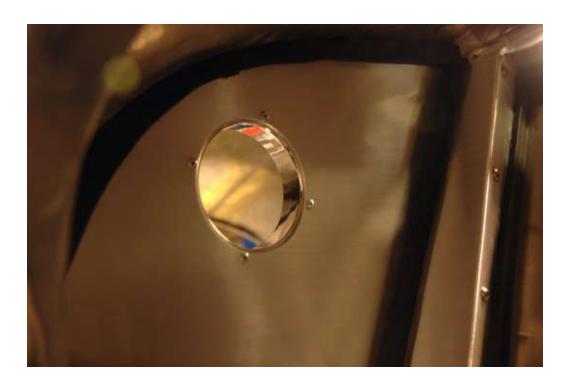
Sir Edmund Hillary



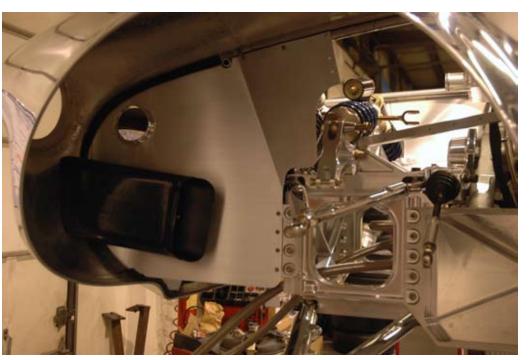
The hood prop rod was made from polished stainless steel.



We made a special serial number for this project. KMA=Kirkham Motorsports America; 5000 was the first serial number in the 5000 series; LJE are Larry Ellison's initials. Only the body on Larry's car was made in Poland.



Fresh air for the passenger comes in through this hole—there is an identical one on the driver's side. Notice the beautifully brushed interior panels.



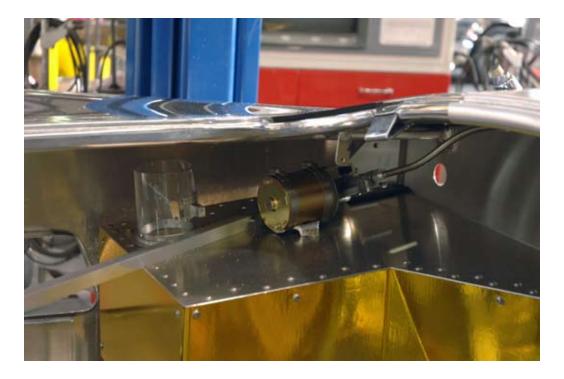
The fresh air flange as seen from the driver's wheel well.



The upper radiator bracket and mounting system is identical to an original Cobra.



We custom made the lower radiator tube from aluminum. All fittings into the water passages on the engine were made from aluminum to prevent galvanic corrosion.



The fresh air can is made from clear polycarbonate. The wiper motor is mounted on the passenger's footbox. The hole in the firewall is for the wiring harness.



Fresh air flexible hose.



We used silver-plated stainless steel aircraft nuts. The nuts are silver plated because they are made for use on jet engines. The silver plating helps to prevent the stainless nuts from galling at the extreme temperatures encountered in jet engines. We used them because they don't rust or gall—and they look pretty sweet.



We made the gas tank from stainless steel. The filler has a breather to let the air escape out of the back of the tank as it is filled.



We made a special, lightweight windshield frame from aluminum. The original windshield frames are made from brass—which is four times heavier than aluminum. We removed weight everywhere we possibly could.



The battery cables are made from thick, 1 gauge cable. The large cable minimizes voltage drop as the car heats up.



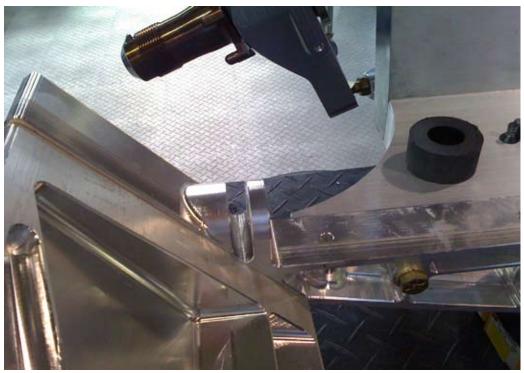
Custom fitting a prototype part.



Even the radiator was custom made.



The inboard seat-belt anchor has a rib that pulls all the way from bottom of the chassis in case of an accident.



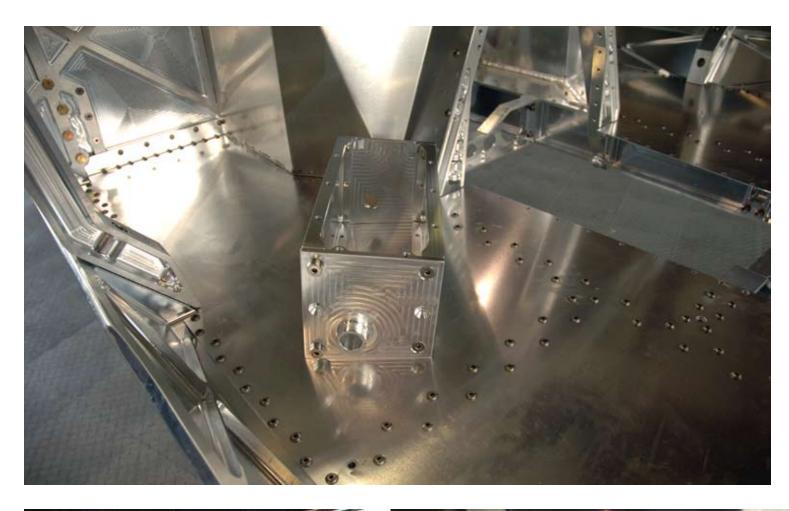
Outboard seat-belt anchor.



The outboard seat-belt anchor allows the seat belt to pivot on the mounting bolt so it cannot be put in a bind and torque anything in case of an accident.



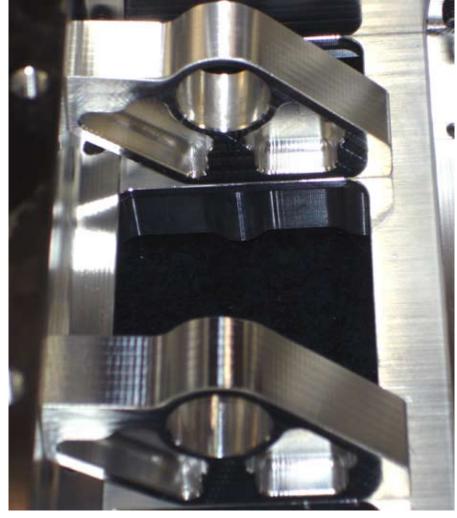
The seat belts were test fit into the chassis to make sure there was no binding.



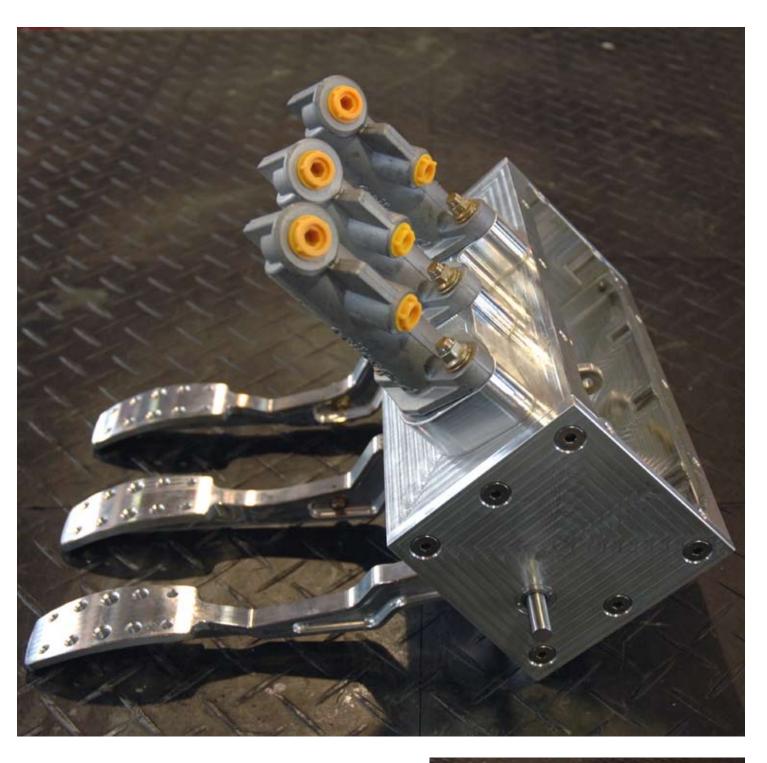
The pedal box (sitting on the floor pan) is just about ready to be installed.

Below: Pedal box pivot pin supports.
These supports minimize flex in the brake pedal pin under hard braking.
We wanted a very precise braking feel in the car. If the pedal box or pivot pin flexes excessively, the driver receives vague feedback from the pedal—making pedal modulation very difficult.

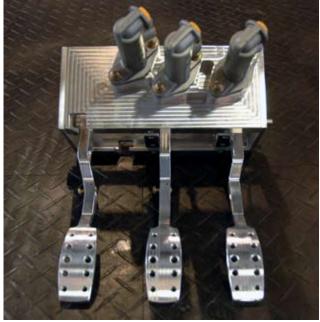


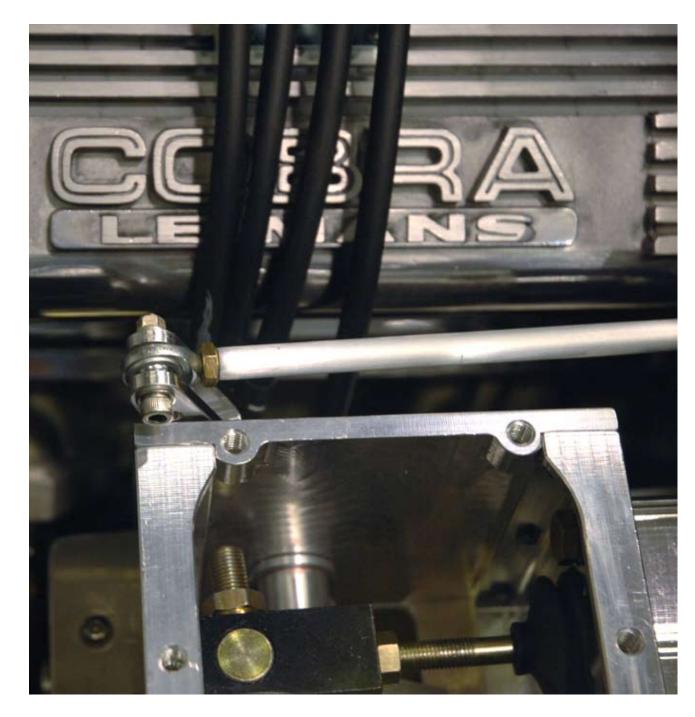


The new pedal box coming together.



We support the pivot pin on both sides of the brake pedal to minimize the pin flex. We also machined away all unnecessary weight in the supports.





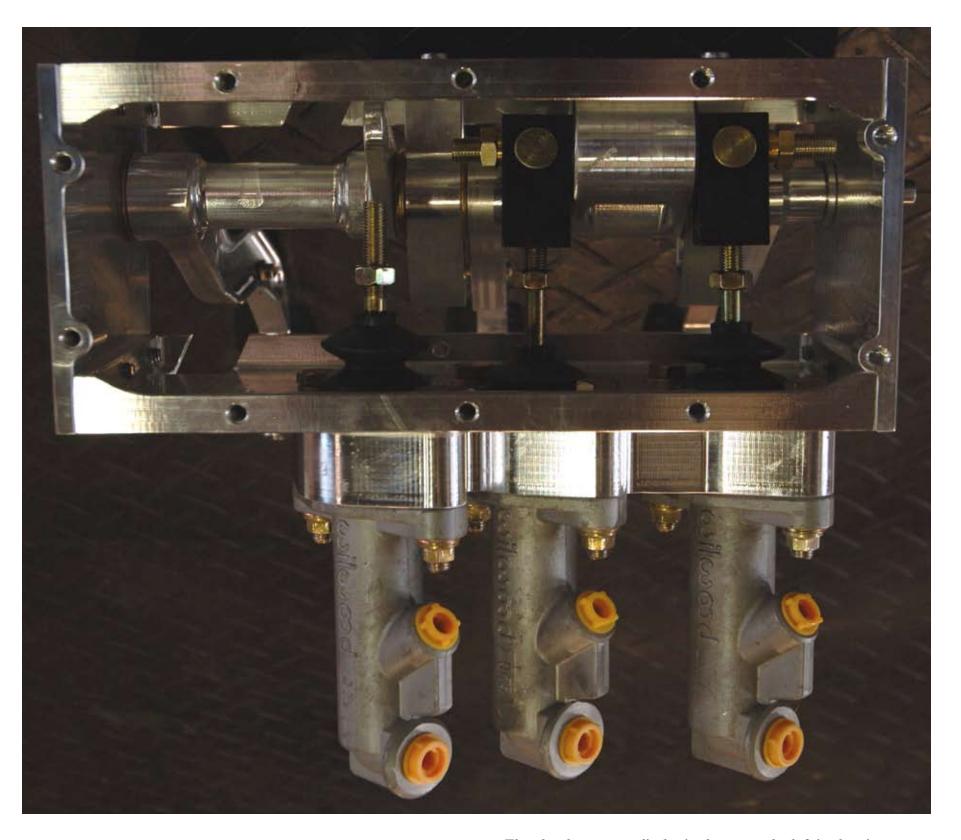


The clutch pedal is on the left and the brake pedal is on the right. The hollow cylinder at the top of the brake pedal is for the brake bias bar bearing.

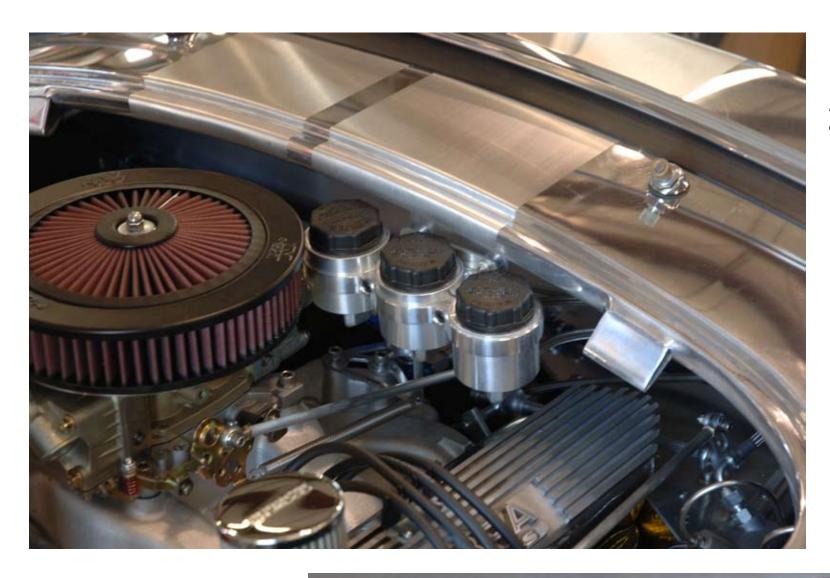
Above: The throttle linkage supports the rod end in double shear. The three different holes allow very fine adjustment of the throttle linkage response speed.

In the upper right photo, we hung the brake pedals from the top of the driver's footbox to provide clearance for the under-car exhaust. The brake pedal arm is machined so it does not have a bend between the brake pedal pad and the pivot pin. If you design a bend in the brake pedal at that point, the forces on the pedal from the driver's foot are not resolved in a straight line to the pivot pin. This causes the driver to unwittingly torque the pedal, twisting and flexing it. Pedal flex dramatically diminishes what a driver can feel in the brakes.

We milled the pedals out of a big block of aluminum to get the exact shape we wanted. We created the offset in the pedal by moving the master cylinder actuating arm down the pivot pin shaft. The pivot pin is then further supported on both sides by internal supports. This way we were able to make the pedal have the absolute minimum amount of flexing and twisting so the brake bias bar could push orthogonal to the master cylinders. Side loading is not a problem for the clutch or accelerator pedals as little force is required while using those pedals.



The clutch master cylinder is shown on the left in the picture. The front and rear brake master cylinders are in the center and on the right. There is an adjustable brake bias bar in between the pushrods of the brake master cylinders. Some racers adjust the brake bias by putting a choke valve in the rear brake line. This is a poor choice because it effectively cuts off the overall braking pressure. It is better to keep all the braking pressure possible in the system by balancing front and rear braking with a brake bias bar—thus keeping the line pressures as high as possible.



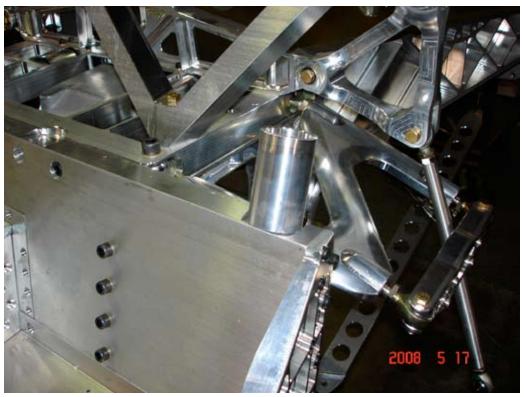
We placed the brake and clutch reservoirs where they were easily accessible for maintenance.

The pedals had to be hung from the top of the footbox because there would have been no room for the exhaust if the pedals were floor mounted (the master cylinders would have been in the way). This posed an extreme engineering challenge because the pedal box must be stiff. Consequently, the pedal box is mounted on a 1 inch aluminum plate that also serves as the top of the driver's footbox.





The "W" brace supports the entire rear substructure of the car. The slots on the top left (in the picture) are for the passenger's shoulder harness. The driver's shoulder harness mounts in the roll bar.

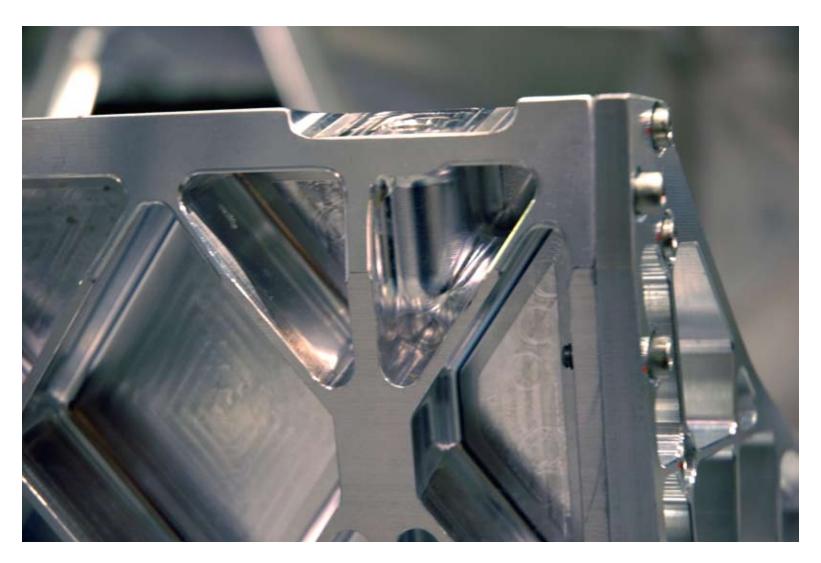


The roll bar mounts to machined cups sitting on top of the rear bulkhead.

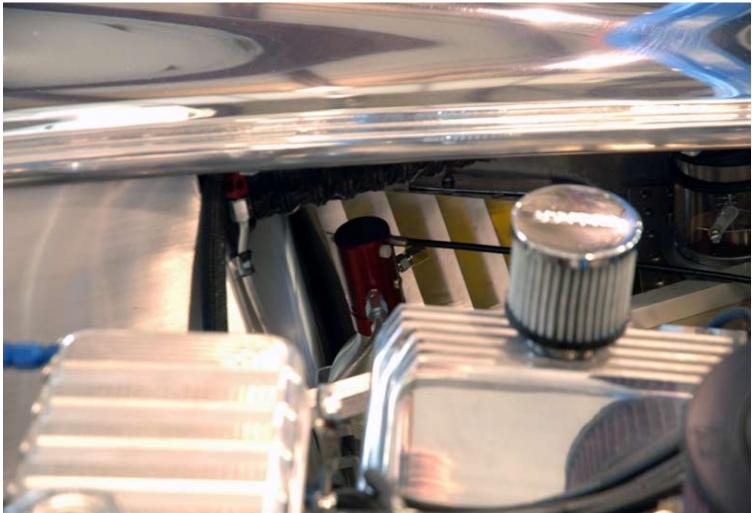


The down brace of the roll bar bolts into the rear substructure tubing—just like an original car. We lathed little bushings and then welded them into the tube. The bushings prevent the tube from crushing when the bolts are tightened.

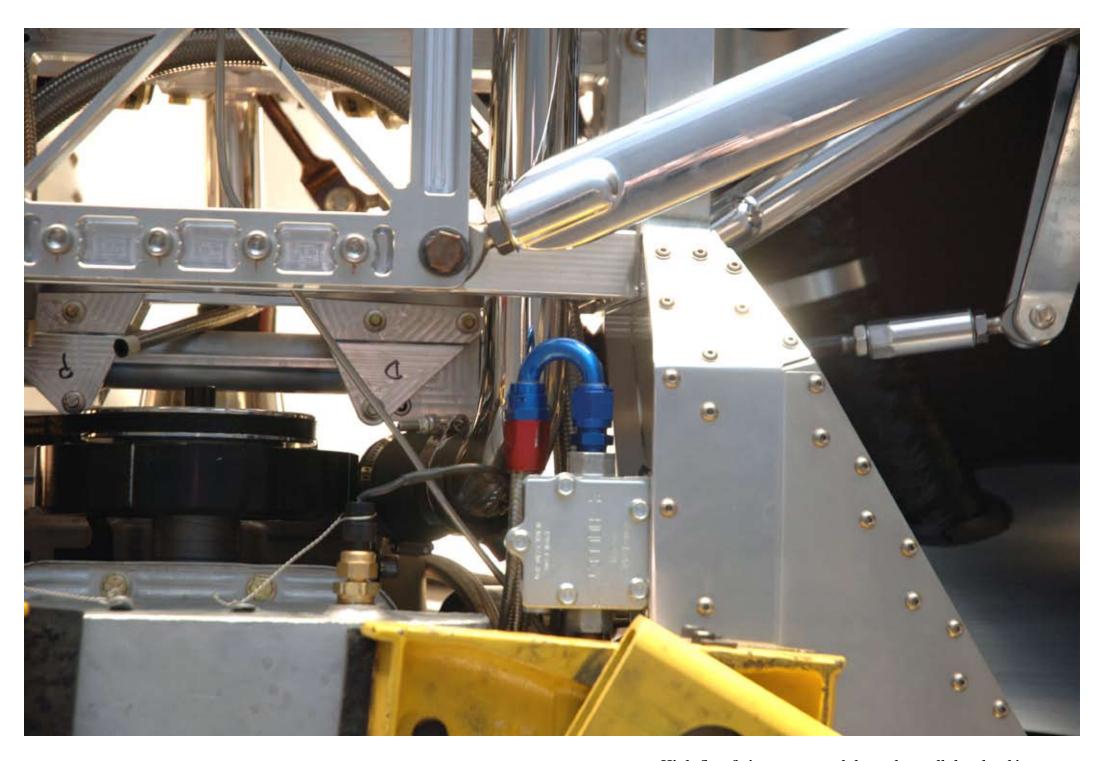
The roll bar is very solidly mounted into the vehicle by resting on—and being mounted to—the rear bulkhead. The cross brace welded in the roll bar is for the driver's shoulder harness.



Closeup of the mounting location of the roll bar cups. Notice the heavy ribbing to carry any loads through the bulkhead and into the chassis.



The halon fire extinguisher is mounted in the engine compartment behind the right front wheel.



High-flow fittings were used throughout all the plumbing systems. Here you can see a high-flow 180-degree fitting on the fuel pump. The fuel pump was mounted in the front of the chassis because the chassis is a closed monocoque structure. Notice the safety wire holding the oil-temperature sensor. Also, notice the "D" and "P" on the steering brackets. They are marked for the "Driver" and "Passenger" sides of the car.

## **TESTING**

To ... not prepare is the greatest of crimes; to be prepared beforehand for any contingency is the greatest of virtues.

Sun Tzu, The Art of War



Notice there is a laser resting at the base of the arms on the lift. The laser shines a dot on a mirror which is taped to the wheel. The mirror reflects the laser onto graph paper on the wall. We removed the shock and moved the wheel up and down to see if the laser dot moved on the graph paper. (If the laser dot moves, the suspension is changing in bump steer.) We then moved the steering rack until the bump steer was minimized. We used this technique to diagnose an elusive alignment problem we had on the prototype car. We finally traced the problem to our first steering rack; the rack was loose in the housing, among other things. We ended up engineering and manufacturing our own rack to solve the problem.

We aligned the car with very little toe-in so the car would "point" quickly in a turn. Toe-in tends to push back on the tires as the car moves forward and lock the suspension in place. The less toe-in the wheels have, the less push back there is on the wheels and the more critical it becomes to have everything tight. We used spherical bearings on all the suspension joints to keep everything tight—very desirable for a high performance car. Bearings immediately transfer any suspension problems directly to the steering wheel—leaving little margin for error in suspension execution. A typical street car uses a lot of toe-in because of the slop in the rubber-bushed control arms; rubber acts like a huge shock absorber at the cost of precision.



Thomas made some special spring cups to support the car without the shocks. He then bounced the car up and down and find out its natural frequency. With that number, he calculated the proper spring rates.



When we aligned the car, we placed the alignment plates on scales so we could "scale" the car—that is, adjust the individual ride heights to make the corner weights the same.



Here you can see we adjusted the front weights identically to each other. The rear wheel weights are within 5 pounds. Notice the complete car (without body, seats, fuel, and windshield) is only 1771 pounds.



Thomas was a flight test engineer in the Air Force—he loves data acquisition. Here the prototype car is hooked up with G meters, GPS, and a data logger to measure accelerations. The car easily pulls over 1g lateral acceleration.





More testing in front of our shop.

We tested the chassis at speed over railroad tracks to make sure everything was working properly under severe road conditions.

First test drive with the body on the chassis.





Larry wanted his car to be a little quieter than normal, so I downloaded a decibel meter for my iPhone. Here the prototype car is at idle reading 77 dB. Notice the tachometer is at 1000 rpms.



I measured one of our standard cars at 80.9 dB at 1000 rpms. Each 3 dB drop reflects a reduction in 1/2 of noise.



Here is the prototype car at 4000 rpms—92.2 dB.



One of our standard cars at 4000 rpms—94.8 dBs.



Once everything was together on the prototype car, we took it out for testing on the Miller Motorsports track. We had several professional drivers from all classes of racing—F1 on down—test drive the car and provide suggestions. We also asked one of our customers with extensive driving experience, Rick Lee, to evaluate the chassis. He offered many valuable insights.



My favorite comment came from the head of the Miller Motorsports Driving School. After several hot laps, he said, "You know, with a Cobra you run out of chassis long before you run out of motor. With this car, I just kept pushing it harder and harder. I ran out of motor before I ran out of chassis. This has potential for a serious race car."

## **ALUMINUM BODY**

Far better it is to dare mighty things, to win glorious triumphs even though checkered by failure, than to rank with those poor spirits who neither enjoy nor suffer much because they live in the gray twilight that knows neither victory nor defeat.

Theodore Roosevelt



Our employees at Kirkham Motorsports Poland are incredible craftsmen. Photo by Kirkham Motorsports Poland.

In 1988, I heard rumors of a local, elderly gentleman from England, named Dennis Balchin, who worked for Rolls Royce before WWII. I tracked him down and persuaded him to teach me the subtleties of welding thin aluminum sheets together with an oxyacetylene torch. He passed to me his incredible knowledge of panel-beating aluminum into liquid lines and fluid forms—an art that is now virtually extinct.

In March of 1995 I traveled to Poland to explore a bankrupt MiG fighter factory. There, I wandered through the dark, silent hangars which produced 3 MiGs a day at

the height of the Cold War. The once thunderous skies over the "People's Aircraft Factory" were still.

Aesthetics are secondary in dogfights and their MiGs showed it. So I was able to pass along many of those graceful automotive panel-beating skills to the eager Poles who would later become Kirkham employees at the MiG factory. They are true Old-World craftsmen.

The raw bodies for the prototype and the final car were made at our factory in Poland, along with the hood and trunk skins. We completed the hood and trunk lid in Utah. The doors, were completely made in Utah.



Making a hood on a stretch press is much like stretching cellophane over a container of food.



Checking to make sure the aluminum sheet is seated in the far jaws.



Aligning the jaws to grab the aluminum sheet uniformly on both sides.



Closing the jaws to clamp the aluminum.



Stretching the aluminum over the form.



Using a rubber mallet to define the edges of the hood.



Closeup of defining the edges of the hood.



Releasing the hood. Notice the rear cowl form in the foreground.



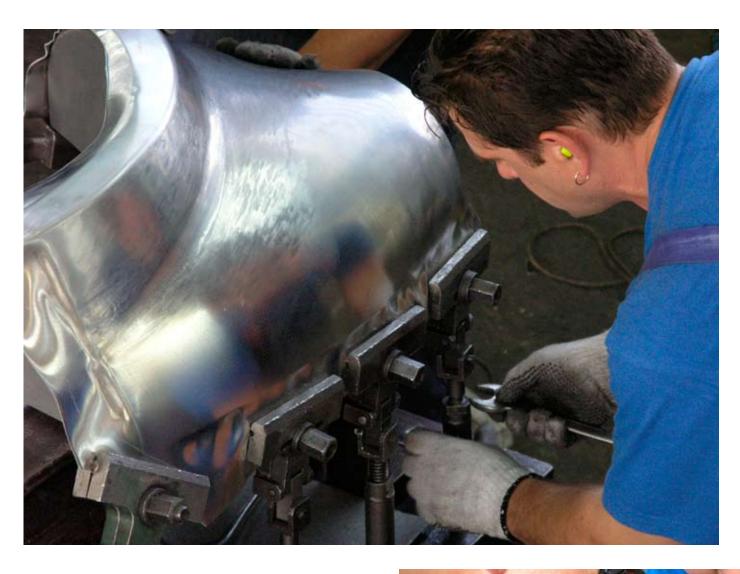
Finished hood skin, ready for trimming. Photos by Kirkham Motorsports Poland.



The left, front fender is made completely by hand. The craftsman is pounding in the "reverse curve" into the aluminum. He is pounding on a "slapper" with a hammer to spread the blows. If you look carefully, you can see this panel is formed by hitting it hundreds of times—all by hand. Photo by Kirkham Motorsports Poland.



In this view you can see the headlight area coming into shape. The clamps hold the aluminum in place while it is being formed. Photo by Kirkham Motorsports Poland.



The holding clamps are tightened as the aluminum is shaped. Photo by Kirkham Motorsports Poland.

The panels are then trimmed and welded together with an oxyacetylene torch. We gas weld panels together for a number of reasons. Gas welding is much faster than TIG welding. Gas welding leaves the metal very soft and malleable, whereas TIG welding tends to make brittle welds. Finally, gas welding leaves a very flat bead that is easy to completely erase with a file. Photo by Kirkham Motorsports Poland.





When we received the bodies for the prototype and final car from Poland, they were rough welded together.



Here is a closeup of the body welds. The Poles are magicians with thin aluminum welding. The welding process warps the panels, and they have to be straightened by hand. Before we can straighten the panels, however, we have to make the 3/4 inch tubing substructure to hold the body in place.



We cut the required 3/4 inch substructure radius right into our custom-made axle. We then machined a pocket in the axle for the clamp die.



We made the "C" axis clamping collet for the push bender.



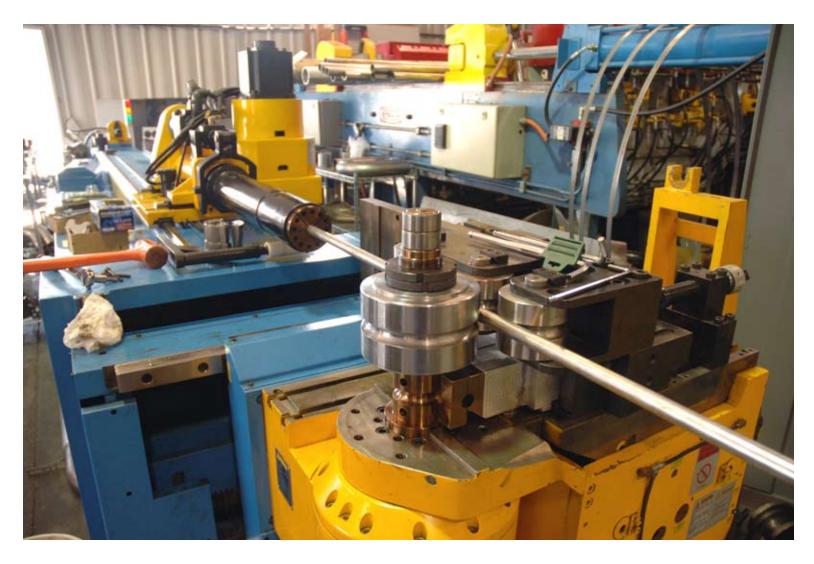
We also had large, graceful arcs to bend. We designed and made three-roller dies as well for our machine.



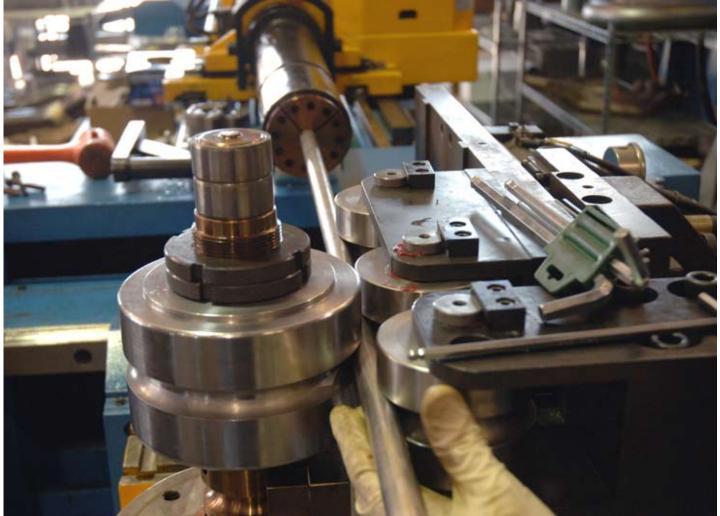
Custom clamp tooling for the 3/4 inch substructure. The working dies were made from 17-4 PH stainless steel.

To support the aluminum body, we had to make a 3/4 inch round tube substructure. The body is mounted on the tubes and secured in its final position before it can be straightened. We used our CNC tube bender to make the substructure. However, our tube bender is designed for 2-inch tubing and the substructure tubing is only 3/4 inch. We called the manufacturer of the

tube bender and asked for 3/4 inch tooling—they said it was impossible to bend the 3-inch radius we required on our machine because our pivot axle was too big. So we designed and machined a new pivot axle and cut our required radius right into the axle. Then we machined a pocket in the axle for the clamp die. We used the actual pivot axle as the new bending die.



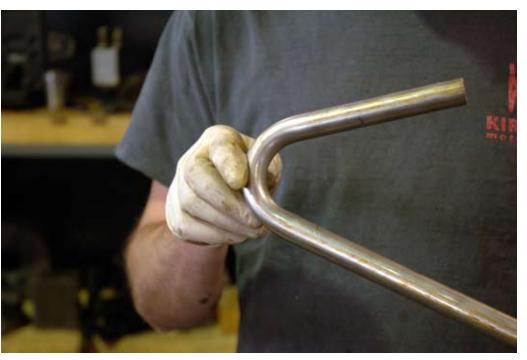
A tube ready to be bent on our CNC tube bender.



The top three rollers are for push-bending large arcs. The small, closest roller (which Sandwich is touching) moves in an arc to bend the tube. The machine can even do variable radius bends.



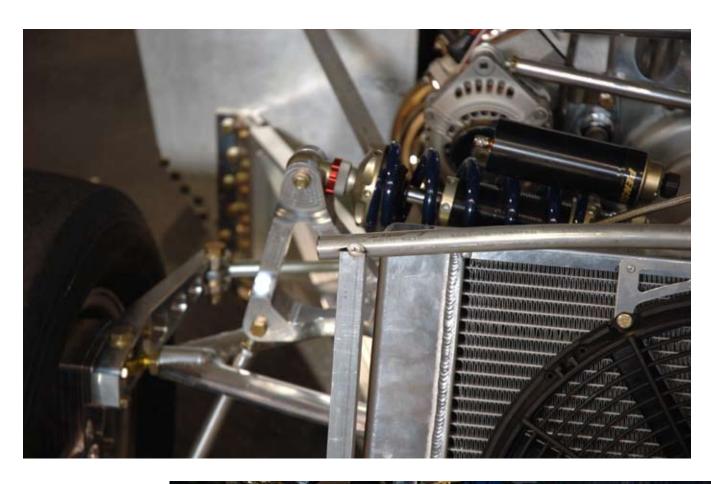
All of our 17-4 parts are heat treated in an oven we specially modified with high-accuracy thermocouples.



The clamps had to be made to very tight tolerances because we were bending heat-treated 6061 T6 tubing without annealing it. We had to buy a special, drawn tube for the bends we wanted.



The CNC tube bender allows the operator to program the tube and virtually bend the part to make sure nothing crashes.



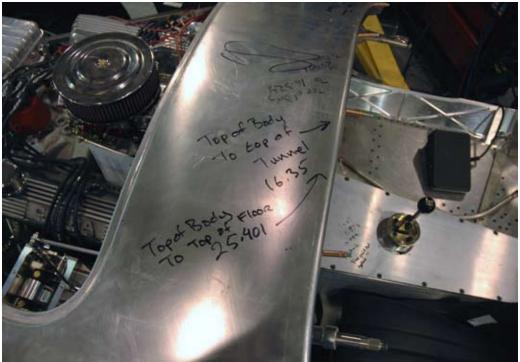
Once we could make the tubes, we decided to make the hood tube first. We had to square the entire car to that point. Notice the tack welds—so they could be easily moved to line everything up.

Once we established the correct height of the leading edge of the hood, we bent tubes and laid them into the underside of the body. We were very careful to have the tubes fit so there would not be any stress on the body when it was mounted.

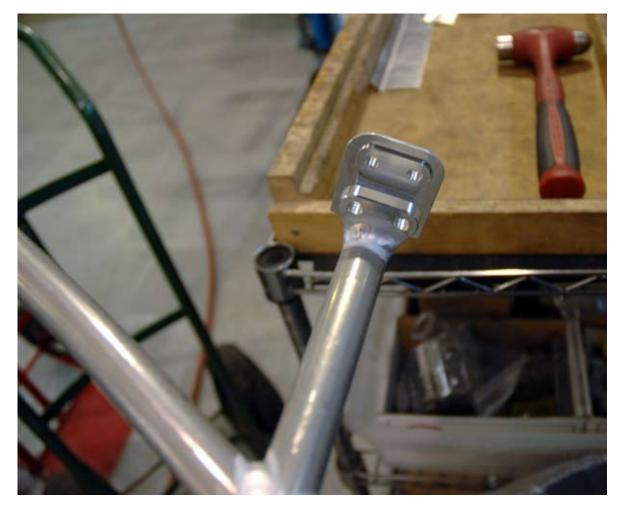




We sheared a piece of aluminum to the exact length from the CAD program. We were very careful to make sure all the edges were square. We placed the sheet of metal on a known base (in this case the top of the front suspension box) and placed another square piece of aluminum on top of it to measure exactly to the tube. Then we knew the body was in the same location as the CAD program.



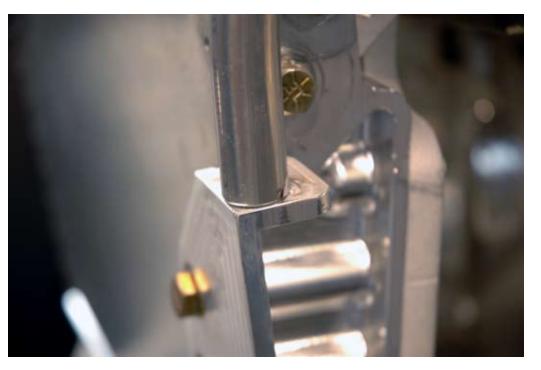
Once the leading edge of the tube was mounted, we were able to pivot the body on the hood leading edge tube. If you look at the writing on the cowl, you can see the measurements we took off the CAD program to position the body in the right place.



Once everything fit, we welded brackets onto the tubes that would bolt the substructure to the billet chassis. The substructure is necessary to support the body.



As we built the substructure tubes, any tube that needed a little tweaking was bent in the press between blocks of wood.



We were very careful to make sure all the tubes lined up. This is the top of the driver's door hinge brace. There is no gap that has to be filled in with weld. If you leave a gap, the hot weld material will shrink and distort the tube as it cools. When the tubing fits together, the opposing part helps to keep distortion to a minimum.



Precise joints...



make beautiful welds.



To make the nicest possible joints, we milled the fish mouths into the end of the tubes.



The front substructure cage after welding.



When everything fit, we bolted it to the billet chassis. (This is the prototype car.)



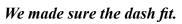
Here is the finished substructure—ready for the final fitting of the body.



We fit the front body clip on first.

Checking clearances.







Checking engine clearances.



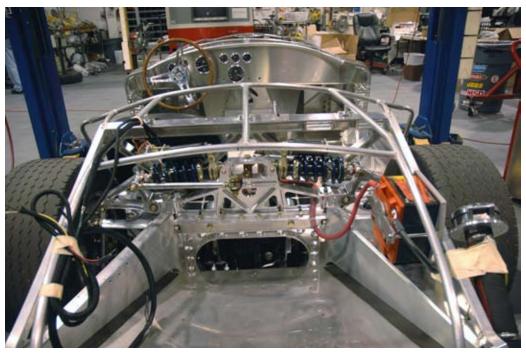
Checking foot pedal clearances.



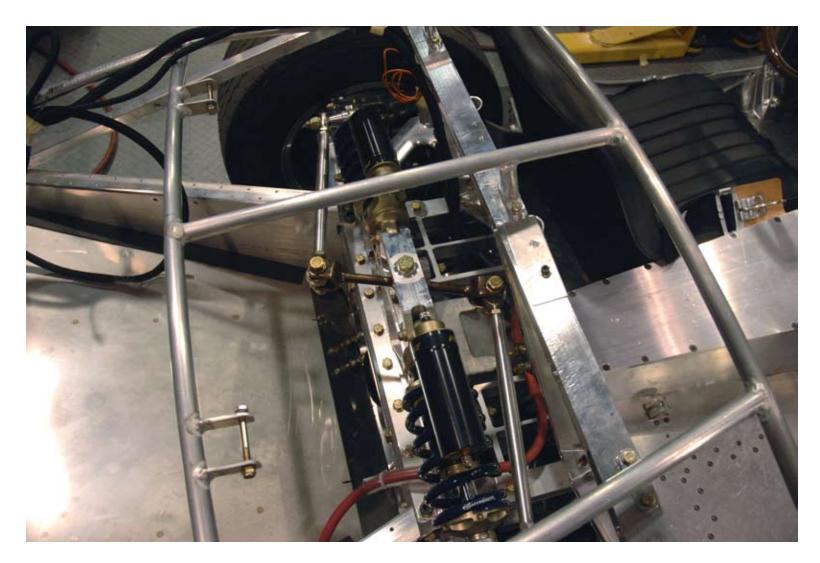
Once everything fit, the final welds were made.



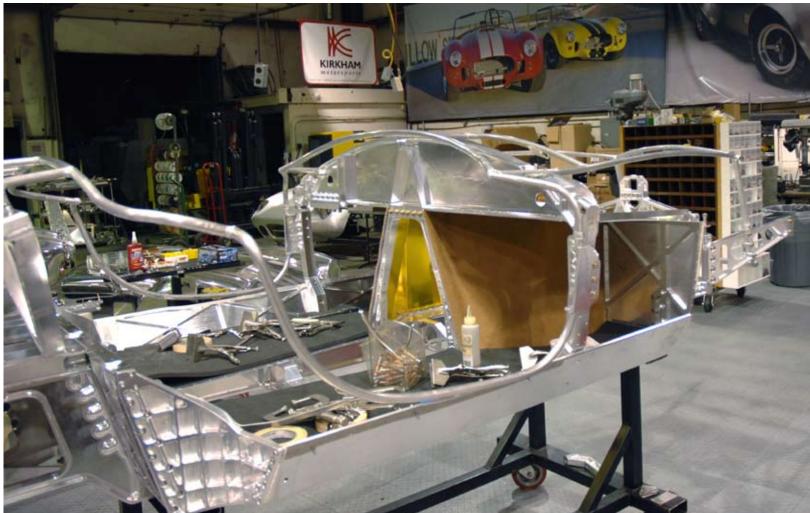
We repeated the same process with the rear body clip.



Here is the finished rear body substructure.



Once the body was fit, the trunk hinge tabs were welded to the body.



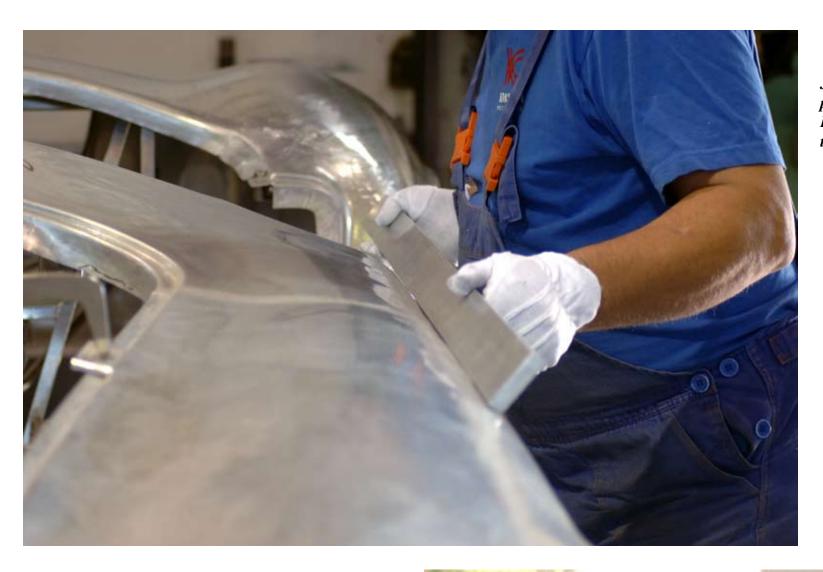
The final substructure tubing work was done with the doors.



Every one of those little dings in the metal was put there by hand when the body was made. Every one of them was removed.



All welds were straightened by hand.



Jozef places a straight edge on a panel to check it for straightness.
Light shows under the edges where the panel is not straight.



He then rubs his hand over the surface of the metal. An experienced craftsman can tell the subtle differences between high spots and low spots. A hammer is typically used to do the gross straightening of the panel. His left hand is holding a "dolly" or a heavy piece of metal that generally conforms to the shape of the panel to back up the hammer blows and help straighten the metal.



Once the panel is roughly straight, a "slapper" is used. It has a large, broad face to spread the blows over the surface of the panel. Again, he is using a dolly to back up the panel.



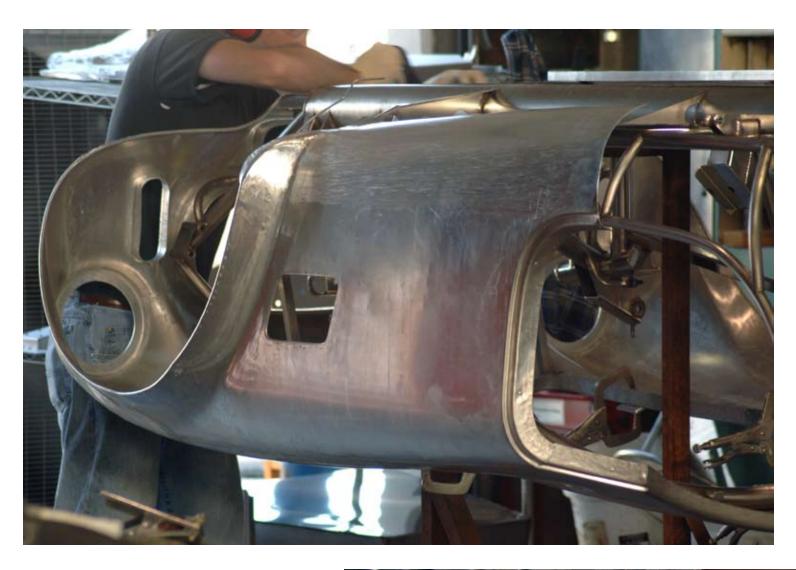
For delicate straightening, we use a "bull's-eye" pic. The long leg under the fender is gently tapped to "pick up" small areas of low metal.



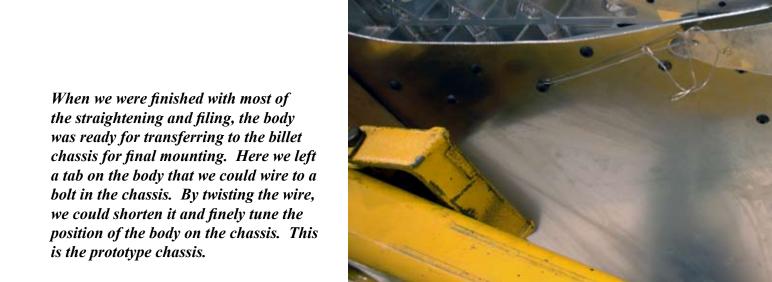
Once everything is straight, we spray some black paint over the panel. When a panel is filed, the black paint comes off the slightly high areas first. This shows which areas are low and need to be picked up. This is where the term "pick and file" comes from.



Expert craftsmen can straighten the roughest of panels. If you look closely, you can see the reflection of his arm in the panel. Some panel beaters wear gloves to reduce drag, allowing their hands to easily slide over a panel. Drag makes it more difficult to feel the highs and lows in the metal.



It is much easier to work on the bottom of the body when it is upside down. All the preliminary straightening work was done with the loose body on one of our standard frames. This allowed for greater access to the body.





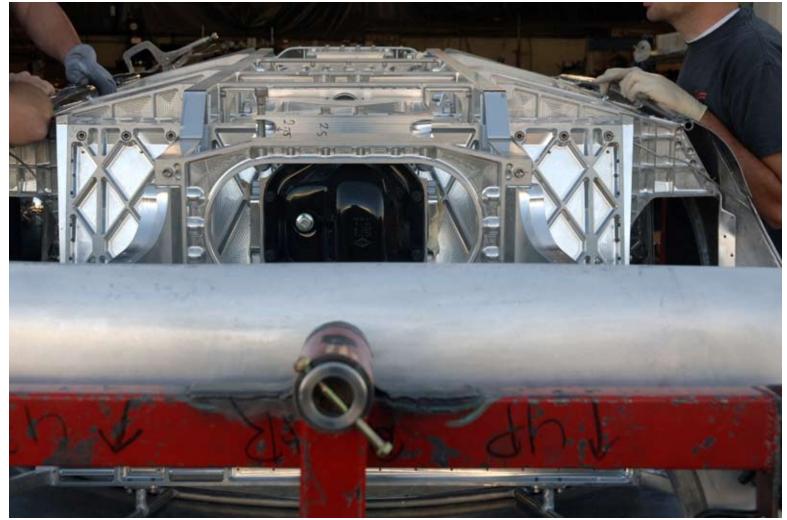
Once the body was positioned, Jozef began to wrap the aluminum over the substructure tubes. Here he is using an aluminum "U" channel as a very large dolly to back up the body as it is wrapped around the tubes.



Once the hood and trunk were wrapped, we put the car on a rotisserie so we could turn it upside down for easier access to the bottom of the wrap. You can tell this is the final car by the gold foil on the footboxes.



The final part of the body to wrap is the area under the doors, or the rocker panels.



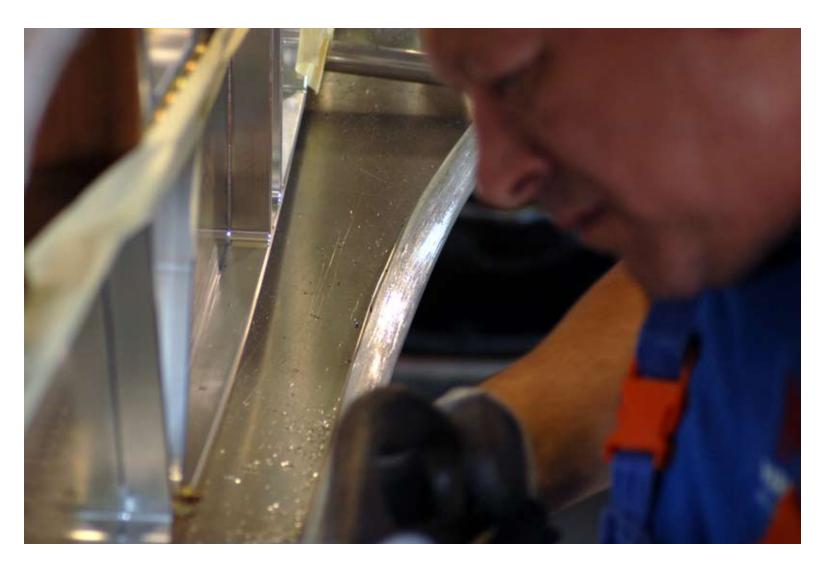
Wrapping the aluminum around the rocker tubes.



Once the rockers were wrapped, they were riveted to the body tube.



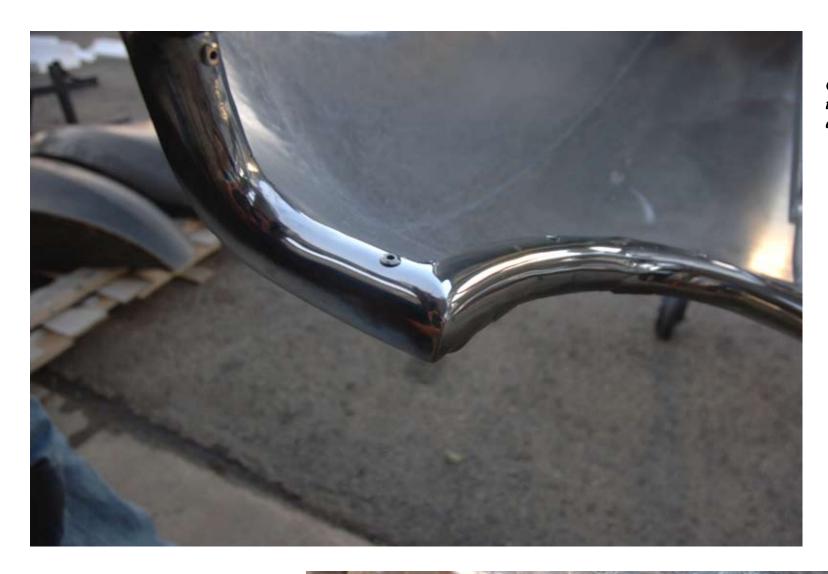
The rockers were "pick and filed" smooth once they were riveted down.



While the car was upside down, we sanded the dash tube smooth.



Polishing under the hood jam tube.



Once all the undersides of the tubes were polished, we riveted the aluminum down permanently.



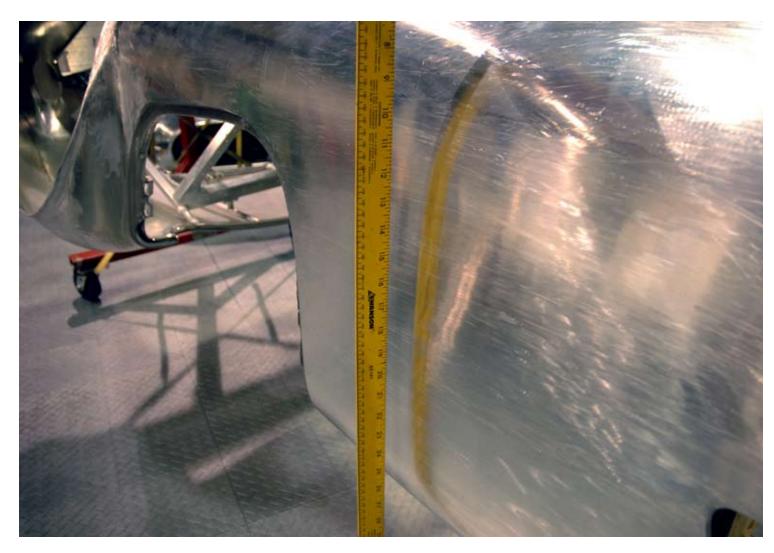
We had a difficult problem with the driver's side of the car. It had slightly too much shape in it by about 1/8 inch. So I took a torch and heated up small spots in the fender. As they heated up, they expanded. While they were hot, I smashed them with a hammer and literally shrunk the panel (tricks I learned from the old Rolls Royce panel beater, Dennis Balchin).



Once the panel was shrunk below the size we needed it, we began to coax it back out to shape.



Aluminum is an amazing material. Notice Jozef's reflection in the panel after he pulled the panel back into shape.



You can see by the reflection of the yard stick in the panel it is straight again.



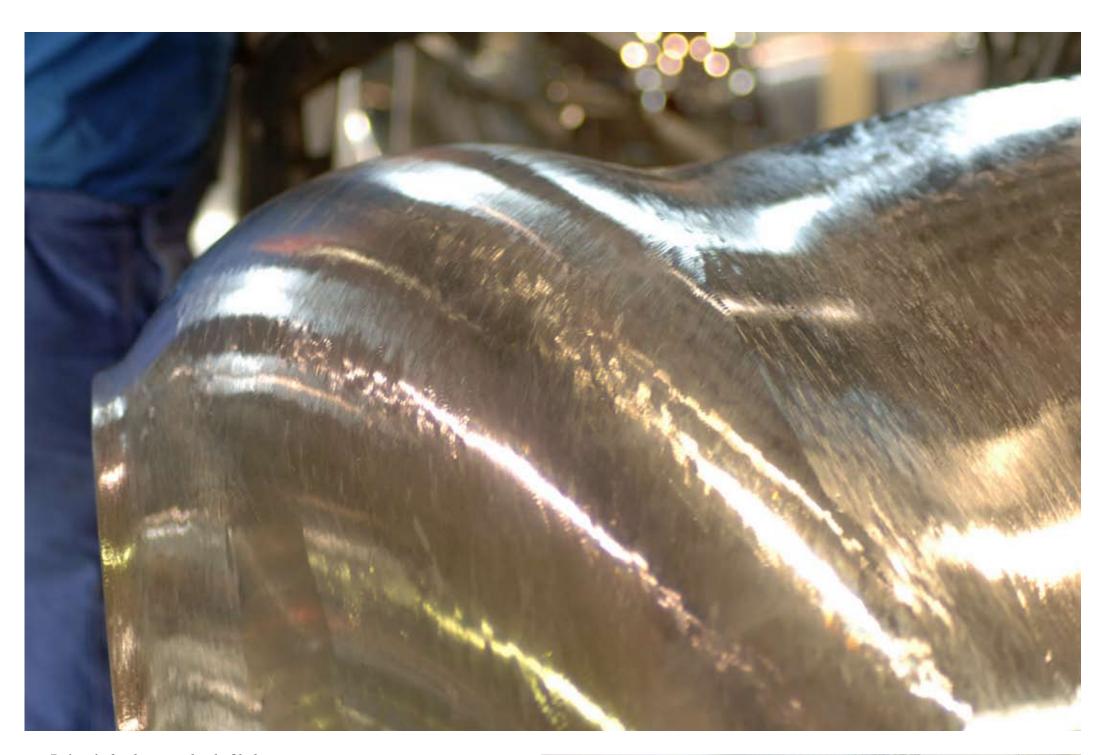
Jeremy and Sandwich welding the body.

Passenger fender completely filed out.





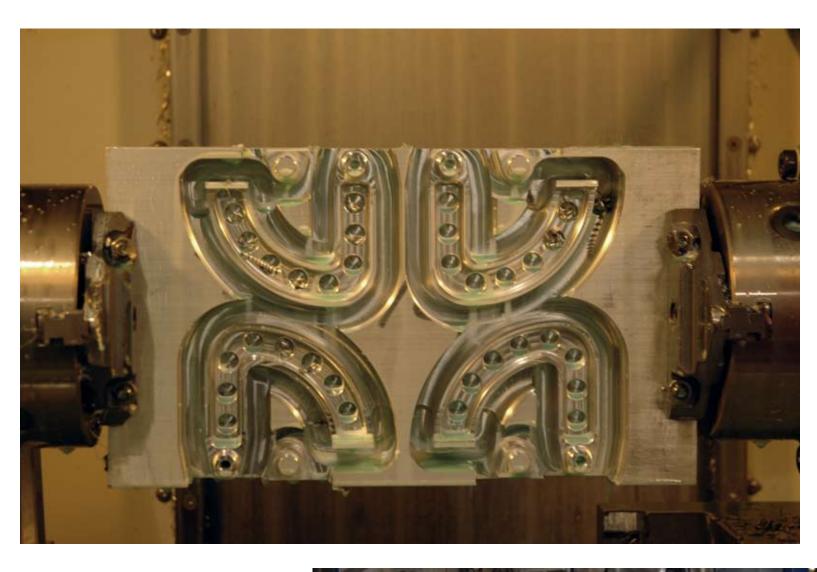
The bottom of the oil cooler scoop was straightened and filed.



Driver's fender completely filed out.

We needed to design and make the hood hinges before we could make the hood.

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The hood and trunk hinges are identical; we machined them from the same plate.



Once the body was wrapped, we were able to make the hood. Here is the initial lay out of substructure tubing for the hood.



The hood hinges need to be mounted to get the hood tubing in the right place.



To support the rear of the hood in the right place, we drilled and tapped a hook into some Vise-Grip pliers then placed the tubes on the pliers. The hood tubes were then cut to length and welded together.



The correct height of the tube is set by this simple tool. The tubes needed to be at least 2 thicknesses of aluminum below the surface of the body—one for the hood skin itself and one for the hood flange.



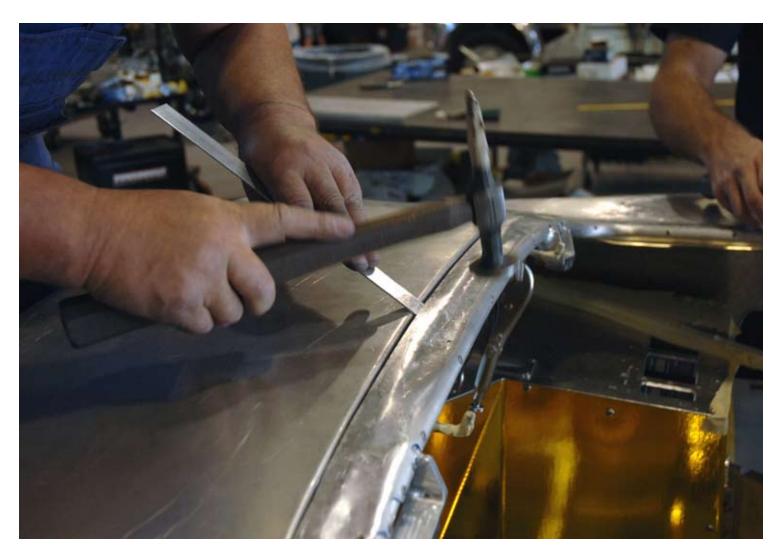
After the tubes were adjusted to the right height, the hood skin flange was cut out and Cleco'd to the hood skin. Clecos are the coppercolored, spring-loaded, temporary rivet you see in the hood.



The flange is then wrapped around the hood tube with a nylon mallet. The nylon doesn't stretch the aluminum out of shape like a steel hammer does. Also, the nylon hammer doesn't mar the aluminum surface. Notice Jozef is holding a dolly in his left hand to support the tubes. Jeremy is holding another dolly on the flange to hold it down as well.



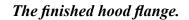
The hood flange is then raised up with a hooked tool.



We hook the lever under the edge of the hood flange and pry against the stiff edge of the hood jam while tapping down on the tube—this lifts the edge of the flange up.



The edge of the flange is tapped up until it is one thickness of aluminum from the body.





A custom scribe marks a line into the hood flange. One leg of the scribe is longer than the other so it can easily ride against the hood jam. The distance of the scribed line is 3/16 of an inch for the desired gap plus 1/16 of an inch for the thickness of the hood skin.



The flange is then trimmed along the scribed line.



Straightening the hood flange with a hammer tapping on a slapper. The hinges and hood latches are mounted to the frame to make sure the hood opens and closes properly.



The hood substructure is then put back on the car to make sure everything is correct.



Cleaning the hood skin to prevent dirt scratches while upside down.



The hood frame is placed on the upside down hood skin and adjusted to fit.



The flange is then clamped to the hood skin.



Marking the distance of the hem with a tool similar to the flange scribe.



Scribed lines.



The hood skin is then carefully trimmed on the outer line.



We use this simple tool to make the hem. The slot is just wider than the thickness of the hood skin.



The depth of the slot is exactly the distance required to make the hem. We then bend the hood skin up 90 degrees. We work the bend in gradually to minimize stretching the hood skin.



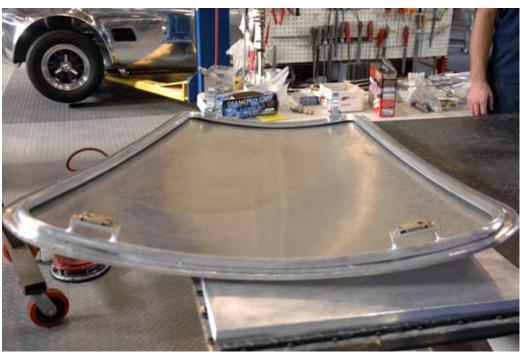
Next the hem is flattened with a hammer and dolly.



The half moon dolly is shaped to fit into the radius of the hood skin.



Once the hem is straightened out, we take a hammer and strike the edge of the hem to tighten up the radius.



Then we place the hood skin with the hem bent up at 90 degrees into the hood frame.



A steel hammer is used to close the hem 180 degrees and to fold it flat.



Jozef checks the hood jam gaps.



Areas in the jam that need adjusting are marked.



With a steel hammer, we move the hood lines until they fit just right.



The hood and the nose do not yet make a perfectly smooth arc on an original car. The nose needs to be raised by about 1/8 of an inch to make a really clean sweep. This is barely visible and would be almost impossible to see once there are stripes on the car. Building a car body by hand truly needs the touch and eye of a master.



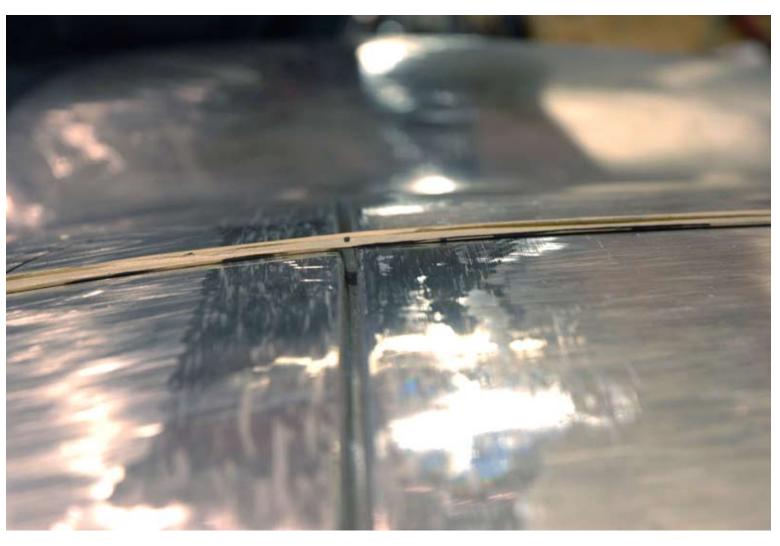
So we took a hammer and finessed the nose and hood until they made a clean, sweeping arc.



The new arc needed to be blended back into the hood quite a distance.



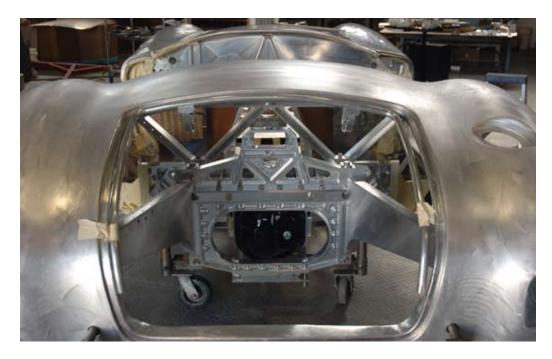
This was done with a hammer and then feathered out with a file.



Here you can see a flexible steel rule (covered in tape so it doesn't scratch our polished cars) lies flat on the arc across the hood jam.

The new nose shape. Now, it is quite graceful.





The trunk substructure tubes are done the same way as the hood—except the trunk is a bit more difficult to do because of the large arc.



Billet trunk latch bracket.



Cleaning the trunk frame getting it ready to skin.



Skinning finished.



Original cars do not have a beautiful transitional sweep from the trunk latch area to the body area below. The transition needed a little bit of surgery to make it right. Aluminum must be annealed to move it very far. First, I coated it with soot...



Then I burned the soot off. The soot burns off at exactly the right temperature to anneal the aluminum. Notice the piece of channel we clamped to the frame so the body wouldn't move around while we were annealing it.



Because we changed the body shape, the trunk gaps moved and had to be corrected. We had to move the trunk line down about 1/8 of an inch. The dark line in the jam is the original 90 bend. We unfolded it then made a new bend 1/8 of an inch farther down.



In the above picture, you can see the edge of the jam is quite round and full of hammer dings. Here we sharpened up the jam and cleaned out all the hammer marks. The white wavy marks are soap. The soap reduces file clogging.



Here I am tapping on a slapper with a hammer, spreading the blows out to do the final tuning of the trunk lines.



When we finished, the trunk body sweeps were as nice as the hood sweeps. You can see the flexible steel rule lies nicely across the jam.



The sides of the trunk jam still needed to be tuned up. You can see they are quite round and not very sharp.

We annealed the side of the trunk jam.





In this closeup, you can see how rounded the edges of the jams were.

After hammering them with a special dolly, we were able to square up the jams quite nicely. Again, the steel rule lies flat across the jam.





This is the custom dolly we made to square up the trunk jam. We got the radius of the body from our CAD file, and then CNC machined the dolly from a block of aluminum.

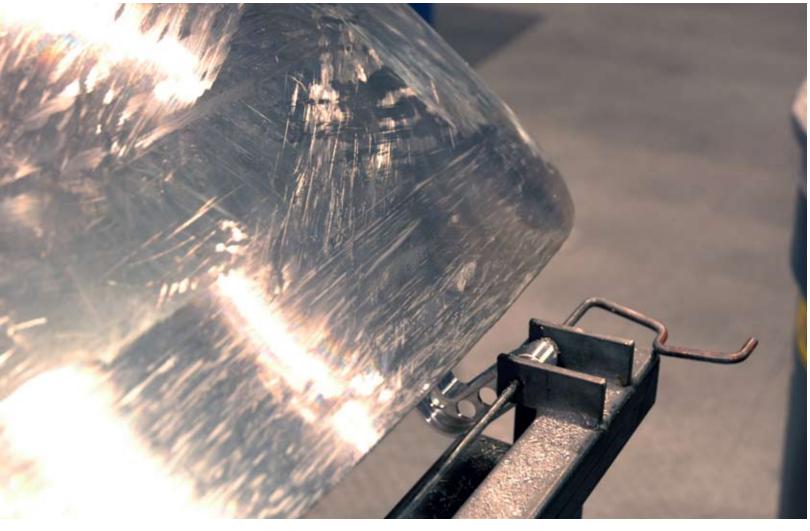
Tools of the trade. Almost all of them are handmade. The big black rubber slapper (third from right) is from our factory in Poland.





Jeremy filing out the trunk jam to remove any errors.

Once the jams and body shape were right, the trunk lid was filed completely smooth.

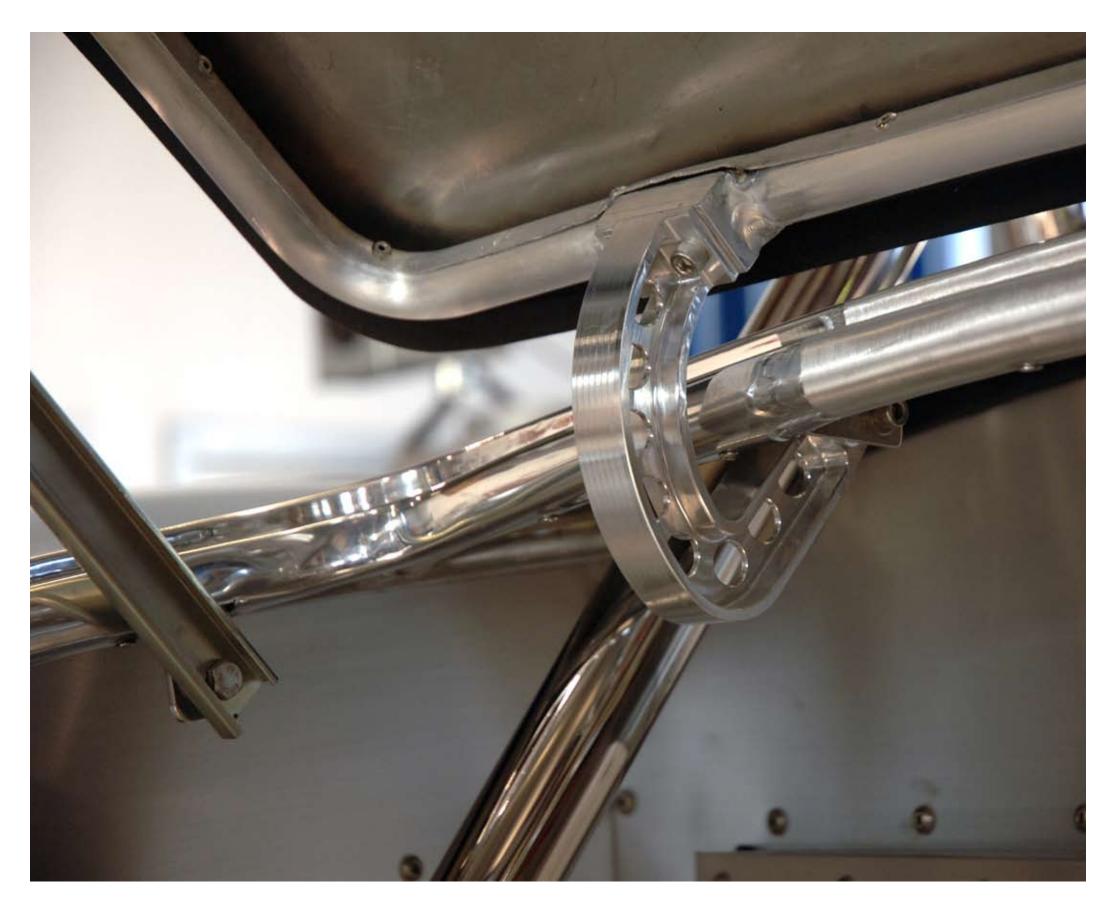




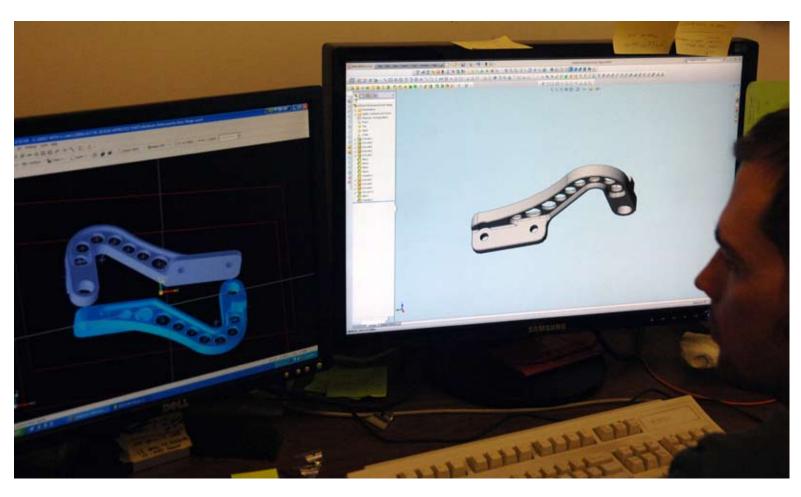
Sandwich fitting the trunk support.

The finished trunk. All the mounting screws are button-head, stainless screws.



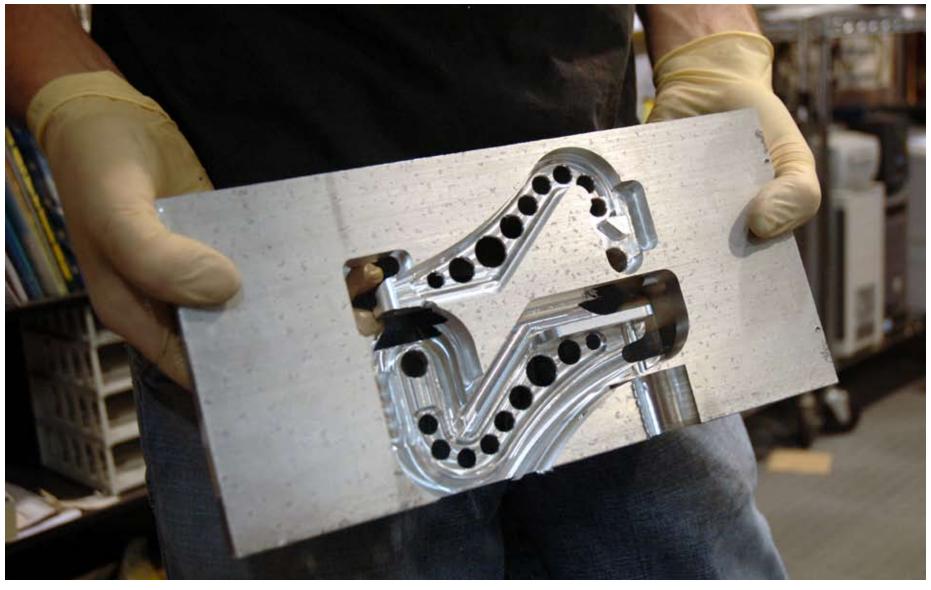


Closeup of the lightweight trunk hinges.

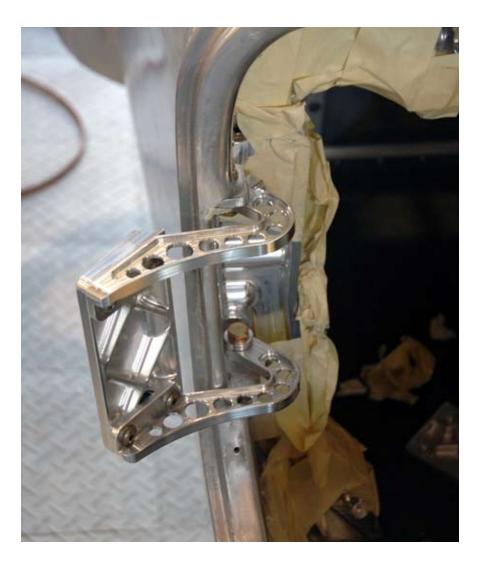


Sandwich designed some beautiful door hinges for Larry's car.

Door hinges coming out of the mill.



The door hinges had to be bolted onto the car before we could build the door.



The door latches below were then bolted to the door frame latch brackets. Sandwich machined these out of billet aluminium as well.





The door striker was bolted to a billet striker bracket and then tack welded to the frame.

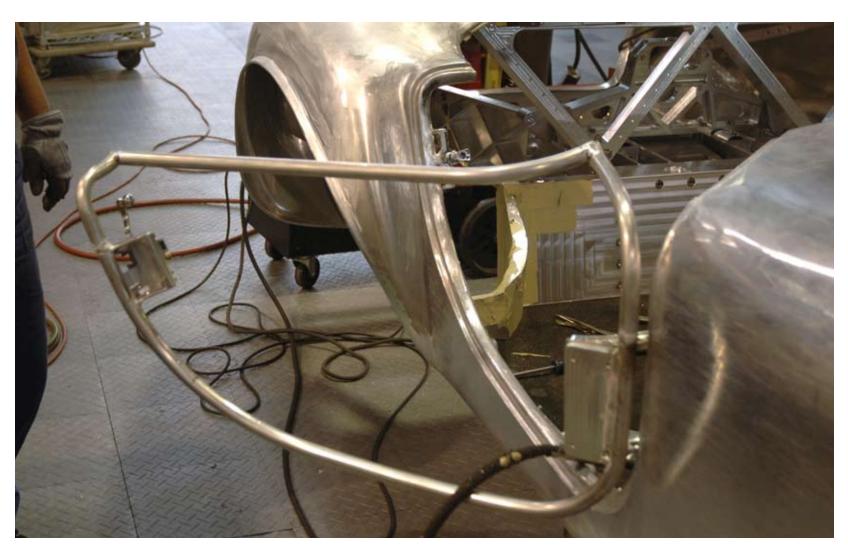
Beginning work on the door frame tubes. The hinge, striker, and latch are functional at all times to make sure the door works.





The door frame sweeps have to line up perfectly with the body.





The doors are a complicated three-dimensional shape.



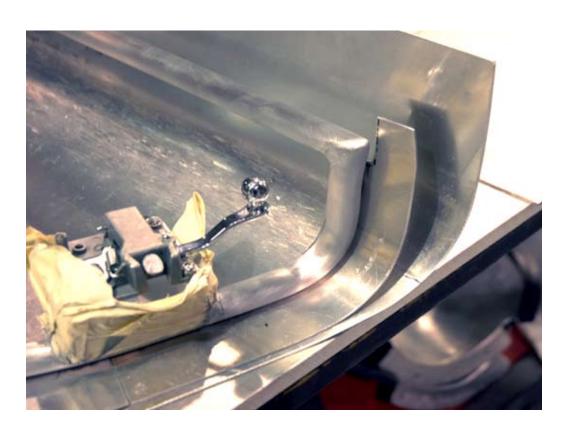
The door latch is tack welded in place as the door is being made.



The door frame flanges being fit to the door.



The large curve of the door is made by bending a sheet of aluminum over a 4-inch pipe.



Fitting the door skin to the door frame for tracing.



Bending the 90 degree hem into the door skin.



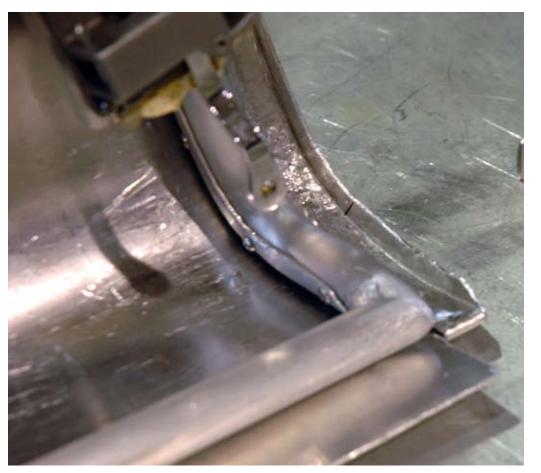
Squaring up the radius. We work on a flat sheet of aluminum to keep everything as square and flat as possible.



Fitting the door frame into the door skin.



Once the door frame is in the door skin, a small tab at the front and rear of the door is bent over to lock the skin into place. Then, the rest of the door can be easily hemmed.





We checked the door gaps one final time before wrapping the cockpit edge of the door.



We made some wooden plates to protect the top of the door while wrapping. The door skin must be held firmly in place to get a nice, tight wrap on the door frame. We use a nylon mallet to minimize marring the door. Any marks will have to be polished out.



We polished the underside of the wrap—just in case anyone ever looks.

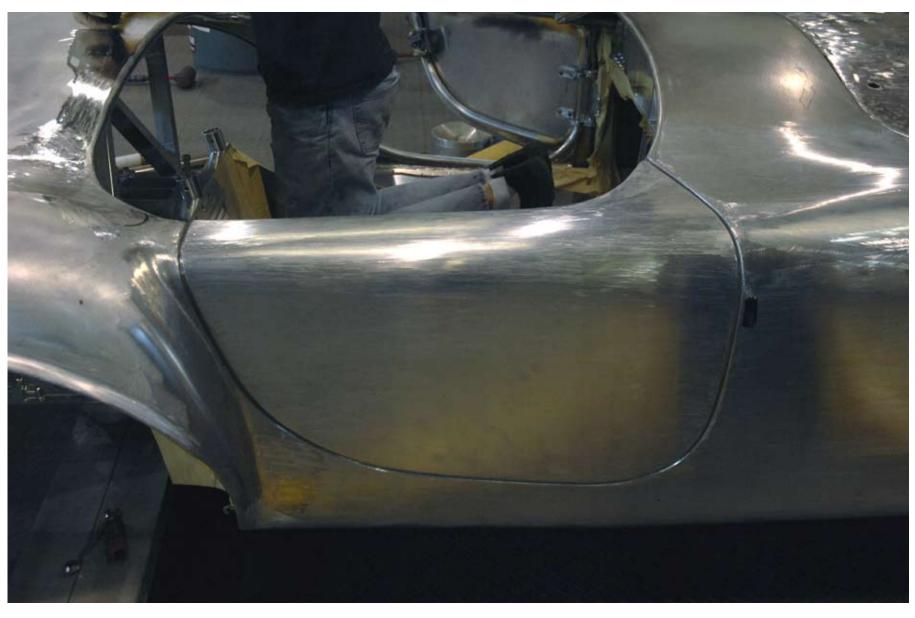


After the door is wrapped, it has to be straightened. The wrapping and hemming put a strain on the door, and bow it inward. We use a long, straight piece of an aluminum "U" channel as a dolly to coax the door straight again.





The door is then filed smooth. When we are finished, all door lines must line up with the body.





Yes, Jozef is filing on a mirrorpolished door. Why? Some waves in the metal don't show up until the panel is polished. We didn't let them slide by—we filed them out.



You can see the slight wave in the door manifesting if you look at the reflection of our building (right on the dark trim line beside the window).



We use a laser to position the hood scoop correctly on the hood. If you look closely at the center cleco in the hood scoop, you can see a vertical laser line and a faint laser mark on the rear cowl tube right by the roll-bar hole.



We use a dual action sander to sand all the file marks out of the car. We start with 120 grit sand paper and finish with 800 grit. We then polish the 800 grit sand paper marks out with Nuvite polish.



Polishing the body.



Right: Sandwich found a few waves even after the body was polished.



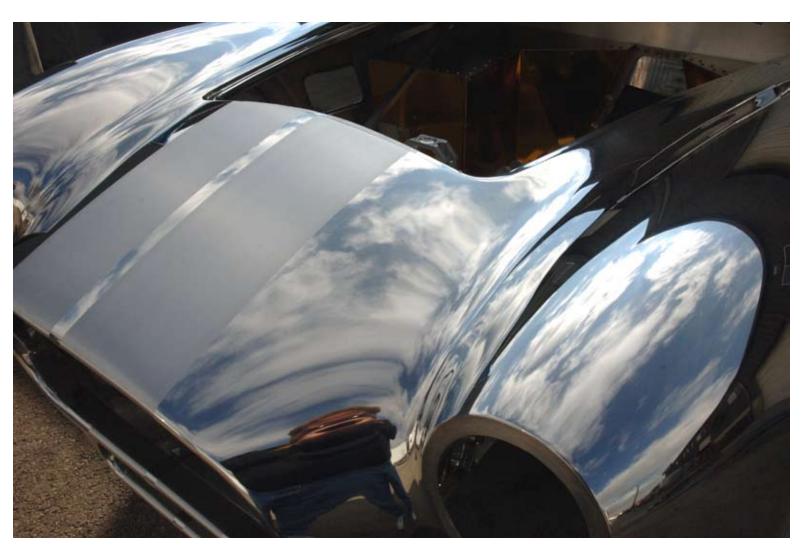
Opposite: We polished out the hood, trunk, and door jams until all visible aluminum had a mirror finish.



You can see the slight wave that needed to be smoothed. It is marked by a black circle.

The final inspection.





Final polishing and striping on the body. The car is completely polished first. Then, the stripes are laid out on the body and sanded into the polished finish with 220 grit sand paper.

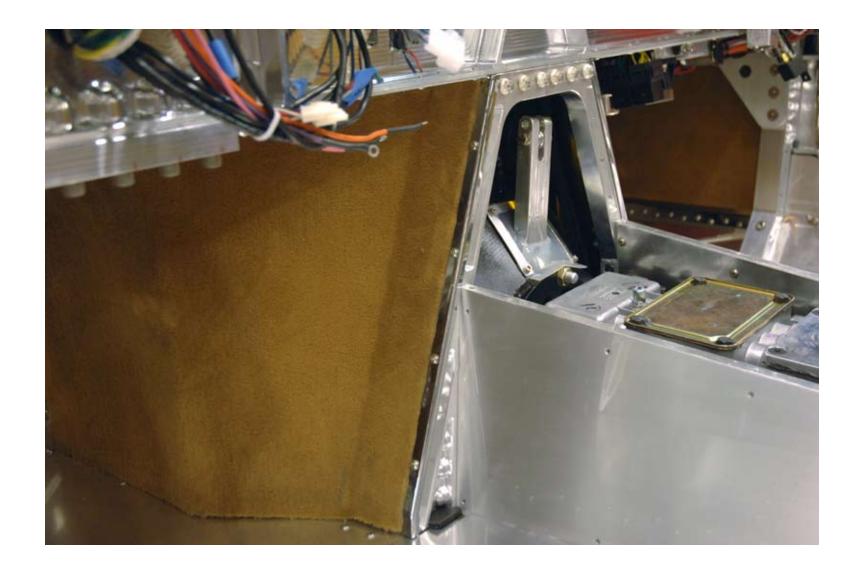


Reflections of Autoweek in the door.

## **INTERIOR**

Simplicity is the ultimate sophistication.

Leonardo DaVinci



Many people visiting our shop lamented that the chassis would be covered up unless someone opened the hood. But all along we planned to show off as much of the chassis as possible. Because we left so much of the interior bare, we had to devise a way to finish the carpet edges. We designed these trim strips to go over the raw edges of the carpet. We cut them out on our water jet.













As we were putting the interior together, I could not bring myself to put the original plastic knobs on the air vents. I threw one to Sandwich and asked him to work his magic. A few hours later these popped out of the machine. We polished them up and then put them on the car.



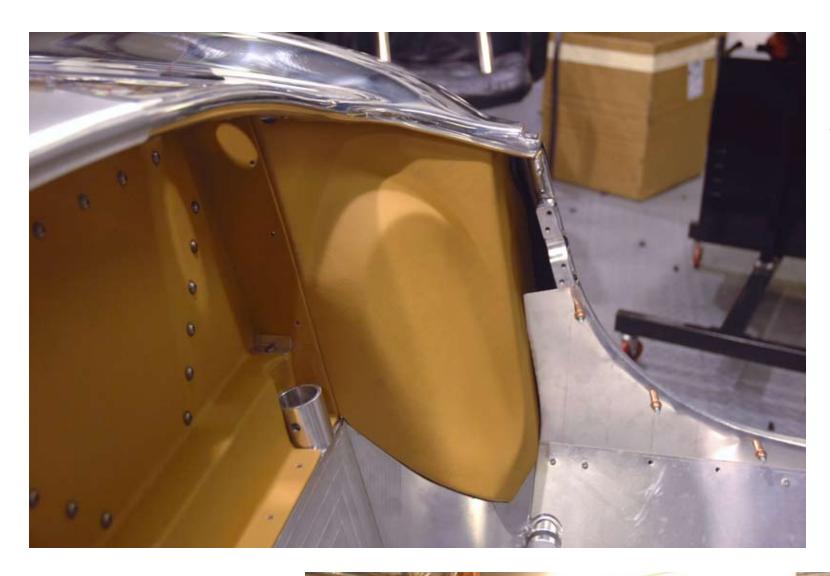
Covering the rear bulkhead in leather.



Fitting the door pockets.



Finished door pockets.



The rear wheel wells were covered in leather and then bolted in with stainless bolts.



We used stainless button-head screws in the rear bulkhead on top of the leather as a nod to the billet chassis. Notice the holes for the passenger shoulder harness in the top, right side of the rear bulkhead (left side in the picture). All the bolts in the interior were either button heads or counter sunk for a flush fit.



Here we are in the final stages of completing the interior. Notice the billet aluminum clutch arm for the throw-out bearing. Also, there are notes written in magic marker on the windshield—standard practice at Kirkham Motorsports.



Here you can see the map pocket behind the seats, as well as how the seat belts mount into the car. The seat belts have all aluminum hardware—we saved weight everywhere we could.





Polished steering wheel hub.

We custom made a clockwise rotation speedometer at Larry's request. Original cars' speedometers rotate counter-clockwise.



The steering wheel was custom sewn from the same hide as the seats and dash for a perfect match.



We made custom billet seat rails. They ride on four bearings each.



Originally, the seats had a plastic knob on the seat tracks...no go. We turned some out on the lathe—and then polished them. Everything had to fit together.



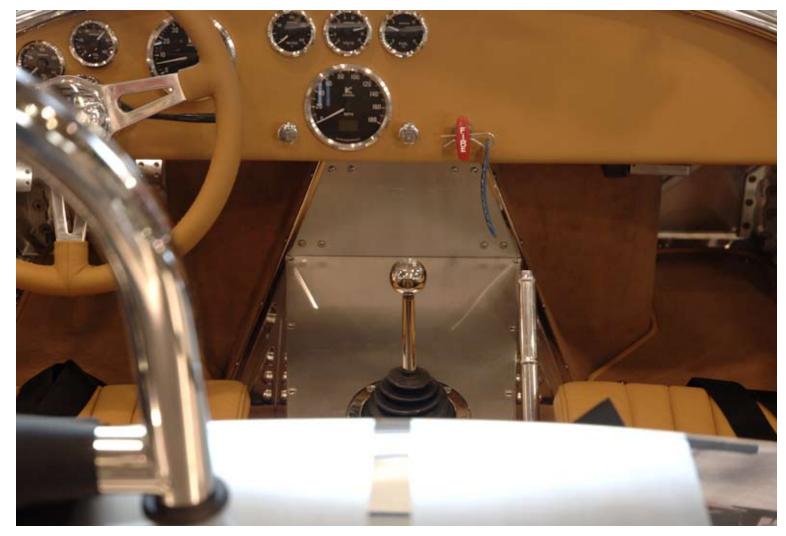
We made the shift lever and knob out of 17-4 PH the same material we made the hubs (and many other parts) from. We engraved Larry's initials in it.



The door hinges were hollowed out to save as much weight as possible. They pivot on stainless pins.



We left the door sill brace open to view so the billet chassis was visible. We bound the floor-mat carpet with the same leather the seats came from. You can also see many of the stainless trim pieces we used to edge the carpet.



We brushed the tunnel and left it with the appearance of bare aluminum. We then covered the tunnel with a clear film to protect it.

## PHOTO FINISH

All we have to decide is what to do with the time that is given to us.

Gandalf, J. R. R. Tolkien

Photos in "Photo Finish, Specifications, and Acknowledgements" supplied by Larry Ellison.

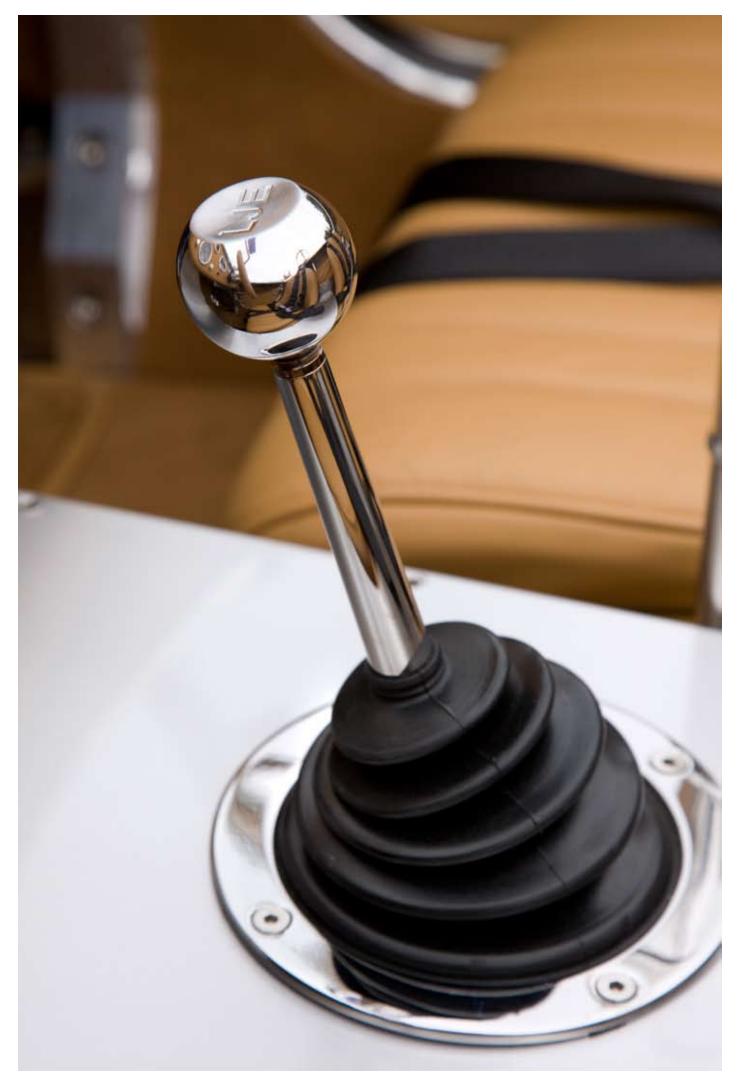






























## **SPECIFICATIONS**

Serial Number: KMA5000LJE

Engine: Aluminum block "Ford 427 FE" stroked to 482 cubic inches

Horsepower: 645.3 at 6300 rpms

Torque: 600 foot pounds at 3000 rpms

Compression: 10.5:1

Carburetor: 4 BBL 830 Holley annular booster double pumper, custom modified

Camshaft: hydraulic roller

Ignition: MSD Digital 6

Red Line: limited 6500 rpms

Transmission: Tremec TKO 600 5 speed

Oil: Valvoline Racing 20W-50; 12 quarts, including filter and oil cooler

Transmission oil: GM synchromesh synthetic; 3 quarts

Differential: 3.42 ratio, 80-90 weight oil with friction modifier for locking differential

Suspension: short arm, long arm fully independent front and rear, push rod activated

1/2 shafts: CV type

Shocks: Penske triple adjustable; high-speed jounce, low-speed jounce, rebound

Springs: Hypercoil; Front, 600 pounds/inch; Rear, 700 pounds/inch

Sway bar: Progressive front and rear

Fuel Capacity: 30 U.S. gallons 91 octane minimum

Aluminum Polish: Nuvite

Tires: Front, Avon 245/60-15; Rear, Avon 275/60-15; 30 psi



# THE BOOK

Luck is what happens when preparation meets opportunity.

Seneca

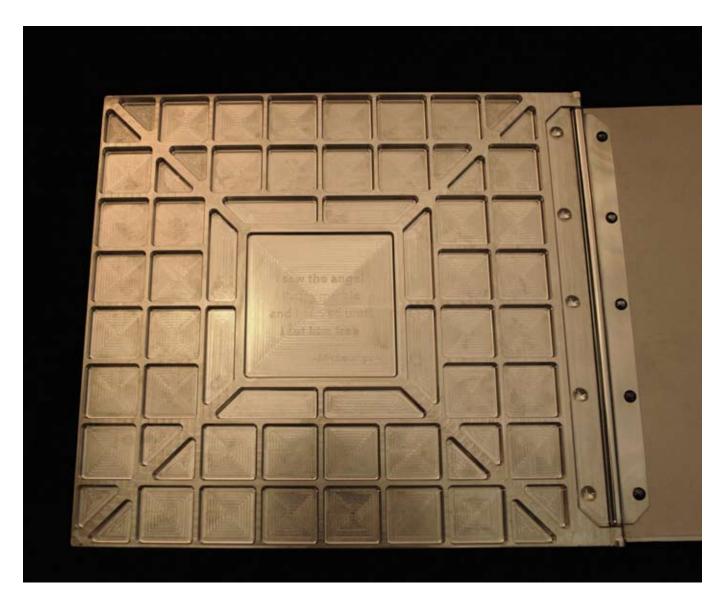


When we finished the car, Larry requested we write a book about the genesis of this project. As the car was completely unique, I decided the book should be unique as well. All the pictures in the book are the raw pictures—nothing was changed, hidden, or fabricated in Photoshop.

The book is representative of the car itself and is a work of art which stands on its own. The front cover of the book is highly polished aluminum—just like the "cover," or body, of the car. It is machined from the same aluminum alloy we used to make the chassis, 6061 T-6. The Kirkham logo is an inlay of

304 stainless steel, the same alloy we used to make the heat shields and exhaust. We heated the inlay up to 1300 degrees in our heat-treating oven, the temperature of exhaust gasses, to give the inlay the same color as the exhaust header tubes.

The Kirkham logo is based around the tire marks left on the ground after a driver makes a three-point-turn. If you look closely, even the tool paths of the end mill overlap in the logo, just as if they were made by an actual vehicle executing the turn. The brushed stripe on the left edge of the cover, refers to the racing stripes on the car. The prototype car is reflected in the cover.





Michelangelo's famous quote alludes to man's creativity.

The front, inside cover of the book is CNC milled to look like the machine work on the chassis.

From the beginning, I planned to create "little details" throughout the chassis that would enhance the beauty and functionality of the car. Those details would be seen only by those who truly searched for them in the car.

If you were looking at the car for the first time, you could not see all the pockets and machine work that went into the chassis to remove excess weight—unless you "opened" the hood. Just like the car, you can not see the machine work of the cover—unless you open the book. Careful, up close, observation is required to discover all the secrets of the car. In the center of the inside front cover, we machined Michelangelo's famous quote, "I saw the angel in the marble and I carved until I set him free." The letters are barely machined into the cover (only a few thousandths of an inch deep), and it is quite difficult to see them—further representing even more treasures to those who search

with careful eyes. The letters in the book were carved with a 0.010" end mill. That is only slightly bigger than the thickness of the pages of this book. Such a tiny end mill is extremely fragile so we had to machine quite slowly. We spun the end mill at 10,000 rpms and were able to take a chip load of only 30 millionths of an inch. The covers took 26 hours to machine.

Notice the little recesses we machined into the far right edge of the cover to clear the head of the custom binding bolts we made. Just like the car, everything had to work seamlessly together. We machined the bolts to bind the book from 17-4 PH and heat treated them to H900. 17-4-PH is the alloy all critical parts on the car were machined from. Their bronze color comes from the heat-treating (aging) process.

For the hinges of the book, we used 304 stainless bolts, the same alloy used in the heat shields and exhaust.



Aluminum will "stress relieve" as it is machined and move slightly. Because the letters were so delicately engraved into the cover, they had to be machined immediately after cutting the center pocket. Here Sandwich had to use a depth gauge after initial machining to get the depth of the end mill perfect.

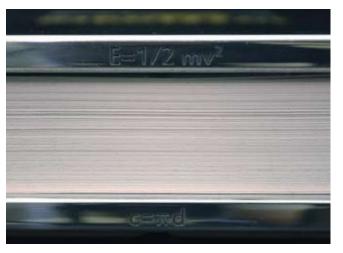


The spine of the book.



F=ma, Newton's famous equation, relating Force, mass, and acceleration, is constantly in the engineer's mind when designing a car. We machined our favorite equations for mechanical engineering into the edges of the book.

F=-kx or Hooke's law. Suspension engineers use the spring equation to calculate spring rates for optimal handling. This equation relates Force to a constant x displacement.



E=1/2 mv<sup>2</sup> is the famous energy equation. Notice Energy goes up with the square of the velocity. High-revving motors have a tremendous amount of stress on the parts.

 $c=\pi d$  describes the circumference of a circle. This is another fundamental equation used in automotive design and engineering. More practically, it describes the circumference of a tire.

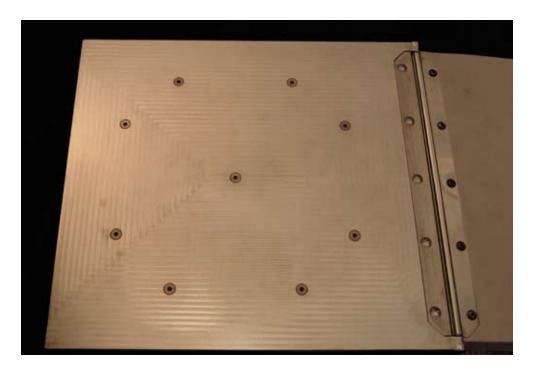


hp=t x rpm/5250 is the horsepower equation relating torque to horsepower. Horsepower goes up with RPM. Torque is mostly a function of the length of the arm on the crankshaft. If you increase the RPM, you increase horsepower. This is why F1 engines spin up so high.

V=IR relates Volts, Amps, and Resistance. Early in the project, we worked on designing an electric car for Larry. This is the fundamental equation used in electricity.



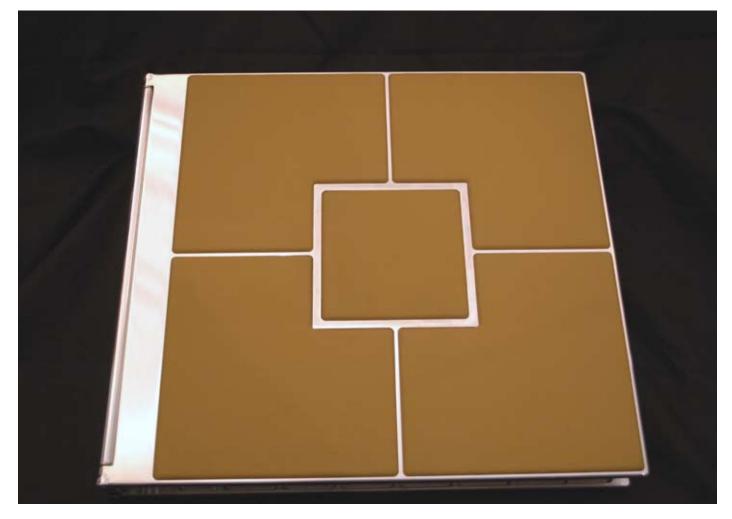
The hinge pins are made from 304 stainless steel bolts, the same bolts used throughout the chassis.



On the inside of the rear cover, we used stainless flat-head screws to secure the leather-covered panels on the back of the book. They are the same screws we used in many places in the interior of the chassis.



The page-binding pins are made from 17-4 PH, the same high-strength stainless steel used in critical applications throughout the car. We heat treated the pins so they matched the hubs.



We covered the back of the book with the same leather used on the interior of Larry's car.

## ACKNOWLEDGMENTS

#### Fear is the thief of dreams.

### Anonymous

I sincerely thank all those who worked so hard to bring this project to life. The late Dennis Balchin spent countless hours teaching me the craft of coaxing aluminum into art. Jeremy Call is a dedicated and extremely knowledgable employee who helped tremendously with troubleshooting and suspension set-up of the car. Jeremy Peterson is an exceptional welder. He was also critical to the final assembly and inspection of all the thousands of bolts in the car. Stephen Kirkham gave vital advice and editing to the book. Many other dedicated employees here in Utah spent hundreds of hours polishing, deburring, and cleaning parts. I am most grateful to the wonderful craftsmen at our factory in Poland who are so talented in sculpting aluminum into unbelievable shapes.

Desire Wilson and the drivers at Miller Motorsports Park gave important technical advice and feedback with on-track vehicle handling during testing. Kenny Hill's unequaled mastery of highperformance materials, alloy selection, and heattreating specifications gave me a glimpse of a new, rarified world in materials science and metallurgy few have ever seen.

Mary Kirkham has traveled to Poland with me many times to help take care of our business while I chase my dreams. Some of my earliest memories are of handing wrenches to my father, Thomas Kirkham Sr., as he worked on our family vehicles. He instilled in me a love of automobiles and taught me the value of hard work. I am most grateful to my wife, Alisa Kirkham, who spent many lonely nights while I was away working on this car and book. Her work was indispensable with the layout and graphic design you see here.

Finally, I am most grateful to Larry Ellison for the complete freedom he gave Kirkham Motorsports to build our dream.

